Neutrino Scattering Results from MiniBooNE

Outline:

- introduction, motivation
- MiniBooNE experiment
- MiniBooNE measurements, results
- interpretations
- further work
- conclusions

INDIANA UNIVERSITY

R. Tayloe, Indiana U.
ECT ν workshop
Trento, Italy, 12/11

Neutrino scattering measurements

In order to understand ν oscillations, it is crucial to understand the detailed physics of ν scattering (at 1-10 GeV)

- for current and future oscillation experiments:
  MINOS, MiniBooNE, T2K, NOvA, LBNE
- especially for *precision* (e.g. 1%) measurements and/or small oscillation probabilities (e.g. 0.1%)

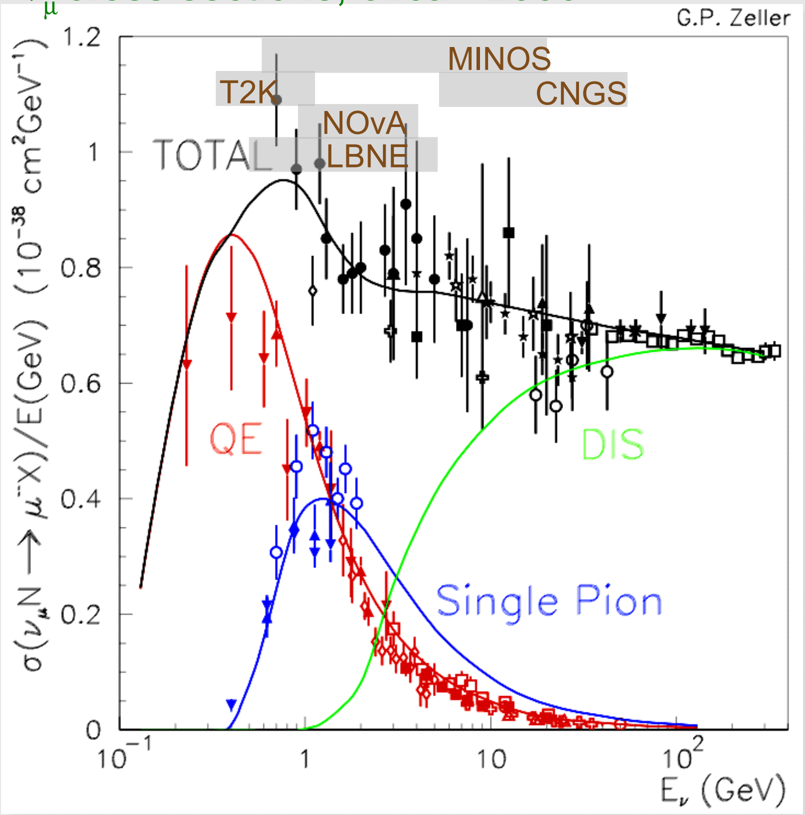
Requires: Precise measurements to enable a complete theory valid over wide range of variables (reaction channel, energy, final state kinematics, nucleus, etc)

A significant challenge with neutrino experiments:

- non-monoenergetic and poorly-known beams
- large backgrounds
- nuclear scattering (bound nucleons)

….

ν_μ cross sections, circa ~2000

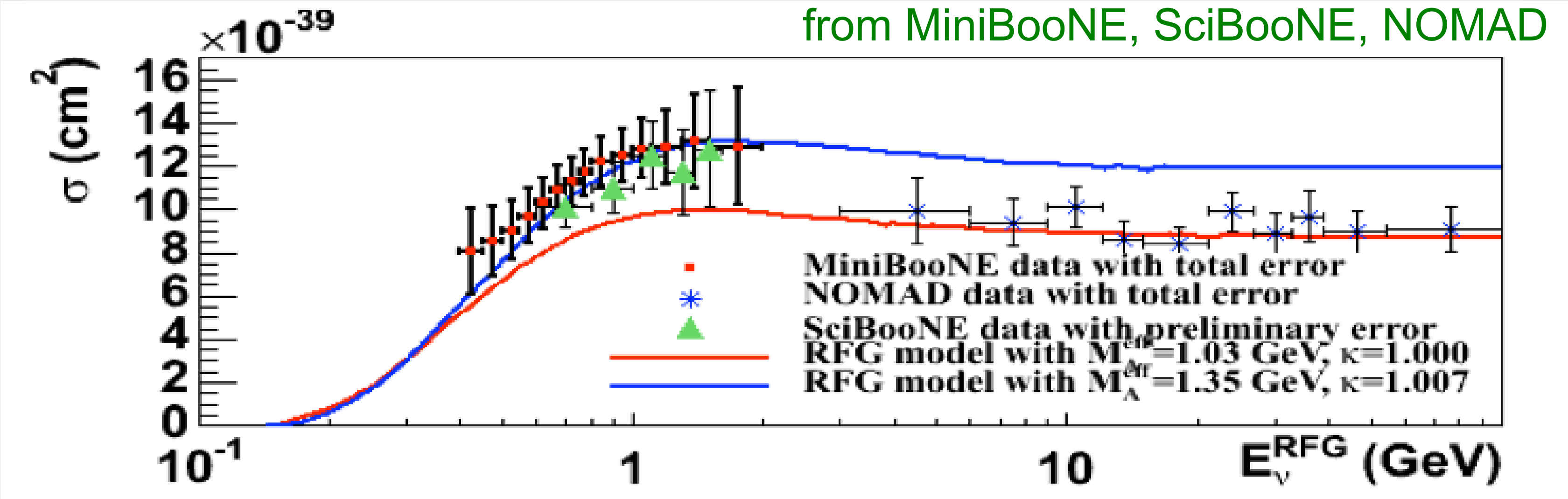


Neutrino scattering measurements

No one said it would be easy...

for example:

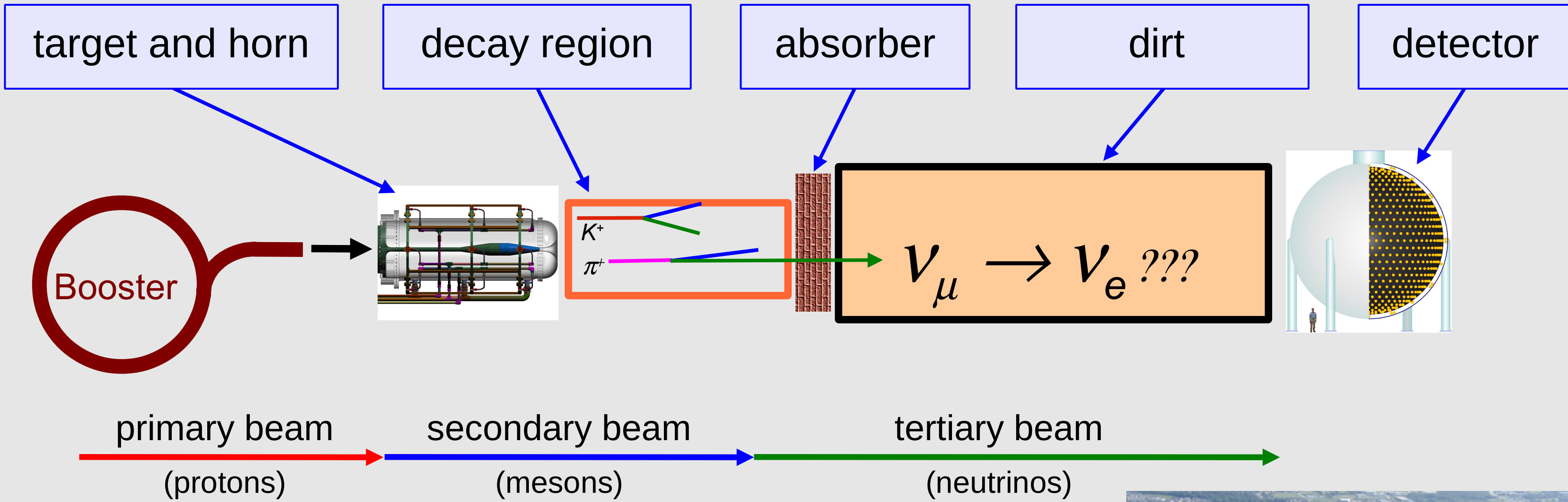
ν CCQE total cross section measurement
from MiniBooNE, SciBooNE, NOMAD



Also,
Revealing some interesting new and/or underappreciated physics.

MiniBooNE experiment, overview

- Built to test the LSND observation of ν oscillations via $\nu_\mu \rightarrow \nu_e$ (and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) appearance.
- Currently running. 2002-2005, 2007 in ν_μ mode, 2005-2006, 2008->=2012 $\bar{\nu}_\mu$ mode.
- ~20 papers published (so far, on oscillations, scattering, details)
  See http://www-boone.fnal.gov/publications/ (All MB theses available there also)



MiniBooNE experiment, ν flux

- Prediction of ν flux is absolute necessity to produce absolute cross sections

- Determined from π prod measurements plus detailed MC (GEANT4) simulations of target+horn (PRD79(2009)072002)

- There was no tuning of flux based on MB data

- Crucial π production measurements from HARP at 8.9 GeV/c beam momentum (as MB), on 5% int. length Be target (Eur.Phys.J.C52(2007)29)

- error on HARP data (7%) is dominant contribution to flux uncertainty

- overall 9% flux uncertainty, dominates cross section normalization ("scale") error

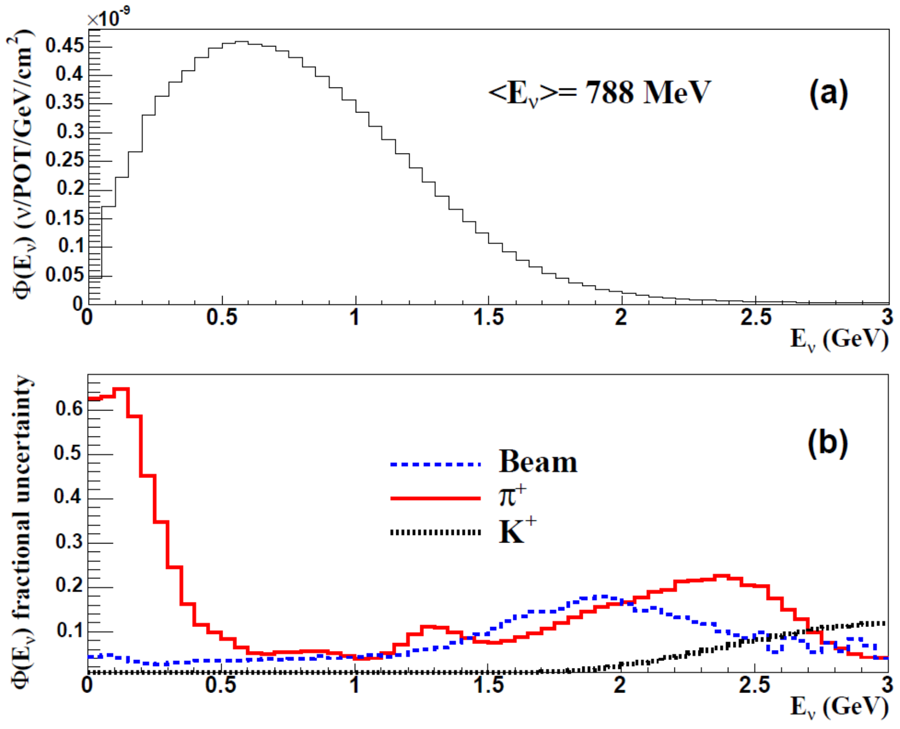
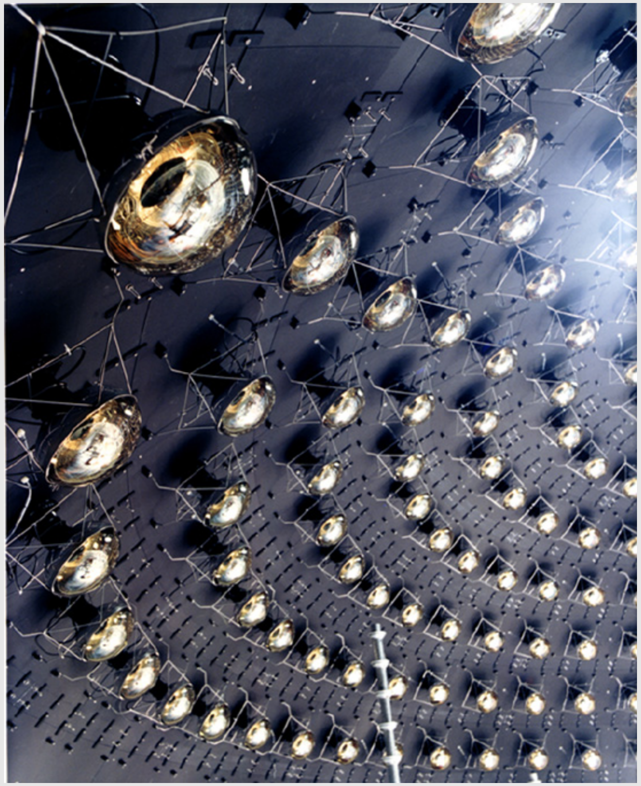
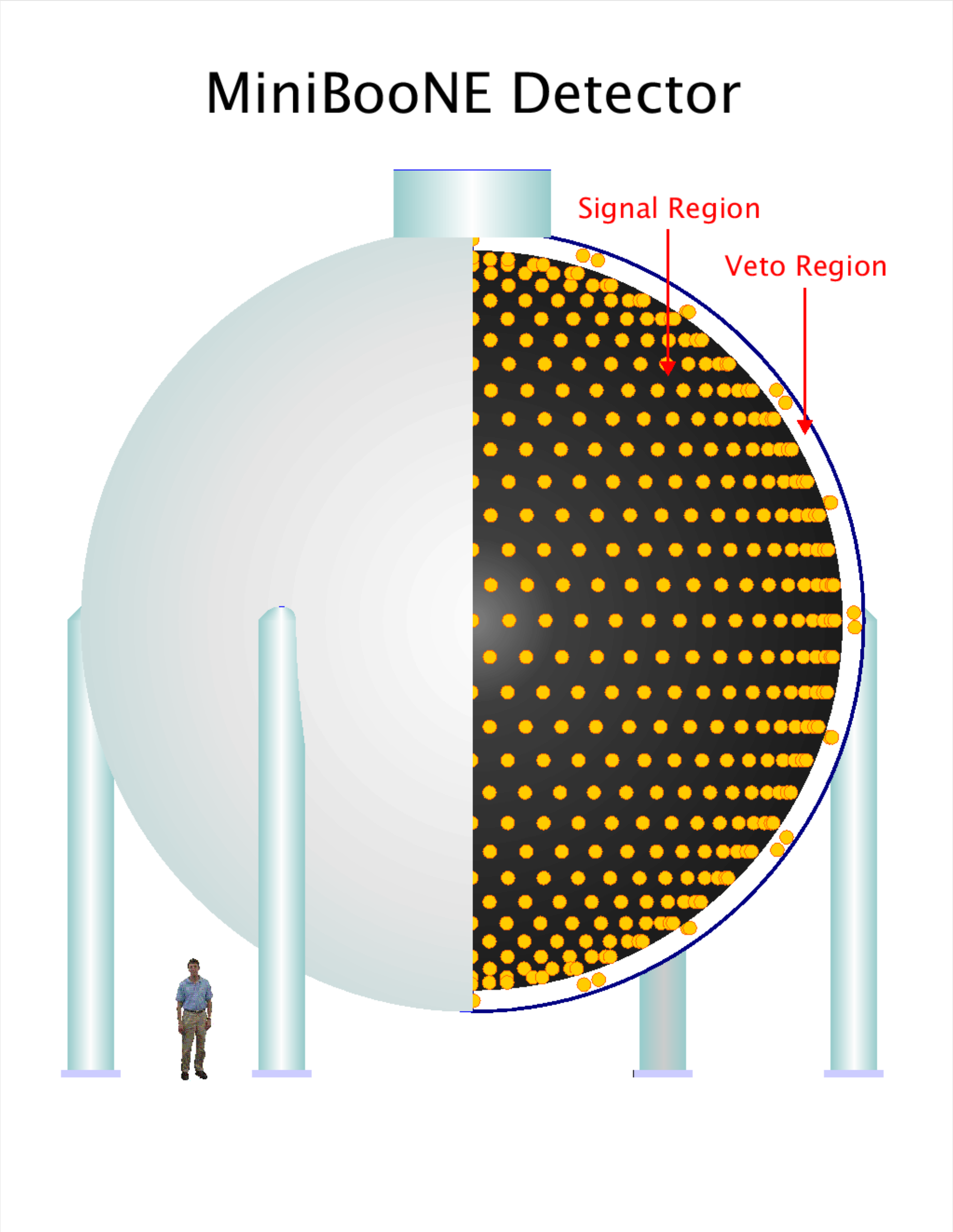


FIG. 2: (color online) Predicted ν_μ flux at the MiniBooNE detector (a) along with the fractional uncertainties grouped into various contributions (b). The integrated flux is 5.16×10^{-10} ν_μ/POT/cm^2 ($0 < E_\nu < 3$ GeV) with a mean energy of 788 MeV. Numerical values corresponding to the top plot are provided in Table V in the Appendix.

MiniBooNE experiment, ν detector

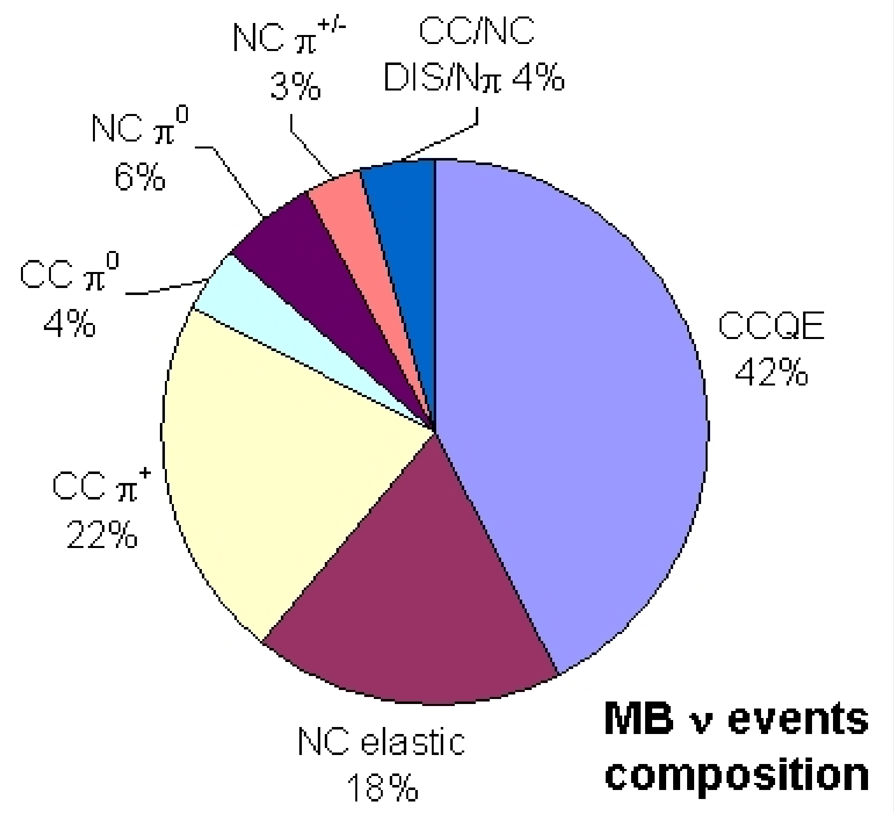
- 541 meters from target
- 12 meter diameter sphere
- 800 tons mineral oil (CH_2)
- 3 m overburden
- includes 35 cm veto region
- viewed by 1280 8” PMTs (10% coverage) + 240 veto
- Simulated with GEANT3
- (detector NIM paper ref here)

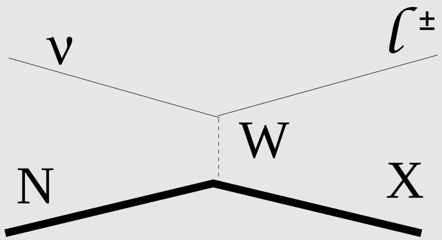




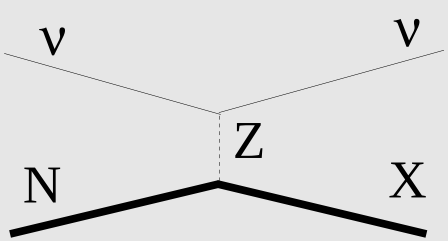
ν scattering channels in MiniBooNE

- ν charged-current (CC) quasielastic (CCQE)
  - detection and normalization signal for oscillations
  - charged-current axial formfactor
- ν neutral-current (NC) elastic (NCel)
  - predicted from CCQE excepting NC contributions to form factors (possiibly strange quarks)
- ν CC production of π^+ , π^0
  - background (and perhaps signal) for oscillations
  - insight into models of neutrino pion production via nucleon resonances and via coherent production
- ν CC inclusive scattering
  - should be understood together with exclusive channels
  - ~independent of final state details
- ν NC production of neutral pions
  - very important oscillation background
  - complementary to CC pion production
- ν NC production of photons
  - a possible oscillation background





"CC":
charged-current



"NC":
neutral-current

MiniBooNE experiment, event reconstruction

- Charged particles in MB create cherenkov and small amount of scintillation light

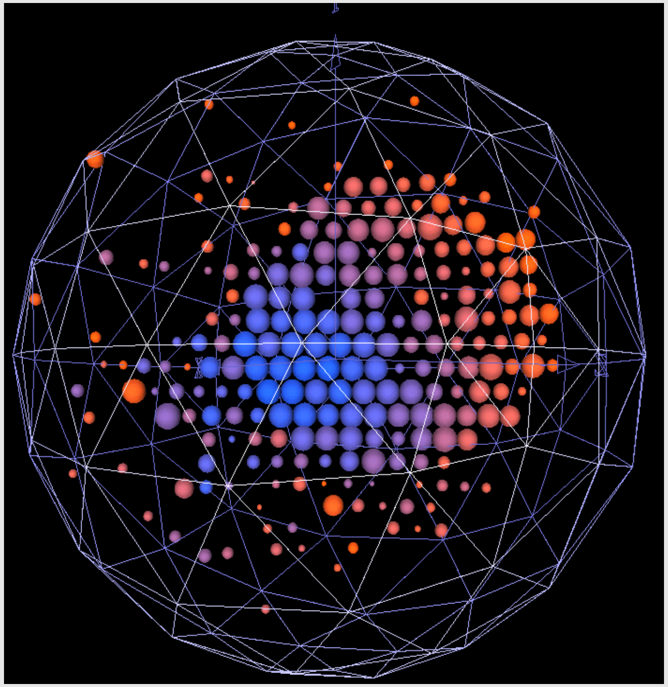
- Tracks reconstructed (energy, direction, position) with likelihood method utilizing time, charge of PMT hits (NIM, A 608 (2009), pp. 206-224)

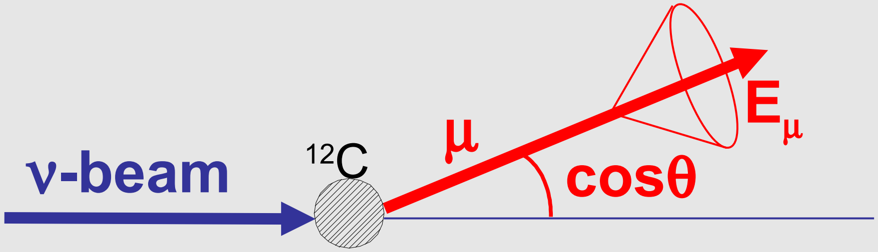
- In addition, muon, pion decays are seen by recording PMT info for 20μs around 2μs beam spill

- In CCQE analysis, all observables are formed from muon energy (E_μ) and muon scattering angle (θ_μ)

- E_ν^{QE} and Q^2_{QE} reconstructed from E_μ , θ_μ with assumption of interaction with bound neutron at rest ("QE assumption")

- For NCel, observables from new proton fitter, no E_ν^{QE} possible and $Q^2_{QE} = 2m_pT_p$



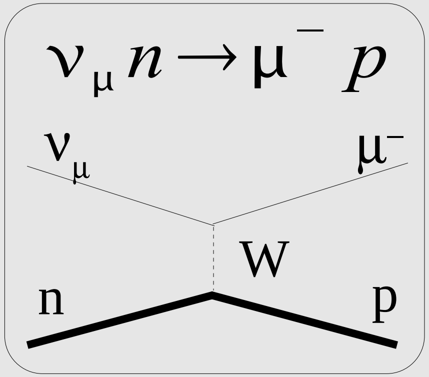


$$E_\nu^{QE} = \frac{2(M'_n)E_\mu - ((M'_n)^2 + m_\mu^2 - M_p^2)}{2\cdot[(M'_n) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu]}, \quad (1)$$

$$Q^2_{QE} = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu), \quad (2)$$

CCQE scattering

ν_μ CCQE



- ν_μ charged-current (CC) quasielastic (CCQE)
  - most fundamental scattering process in ~1GeV range
  - detection and normalization signal for oscillations
  - charged-current axial formfactor

- Historically, “quasielastic” in “CCQE” comes from high-energy ν experiments where muon mass is negligible.

- But has evolved to mean quasielastic scatting from bare nucleons (lightly?) bound in nucleus. How true is this?

- Careful! Can also imply a final state selection for experiments. Important to consider.
  - eg: in MiniBooNE, QE = muon and no pions, no selection on outgoing nucleons
  - in K2K, QE=muon + proton with QE kinematics

  Can result in different measurements.

MiniBooNE ν CCQE analysis

- CCQE experimental defintion: 1 μ^- , no π
- Requires id of stopping μ^- and 1 decay e^- (2 “subevents”)

$$\nu_\mu + n \rightarrow \mu^- + p$$
$$\quad\quad\quad\quad\quad \rightarrow \nu_\mu + \nu_e + e^- \quad (\tau\sim2\mu s)$$

- (No selection on (and ~no sensitivity to) f.s. nucleon)
- CCπ produces 2 decay electrons (3 subevents)

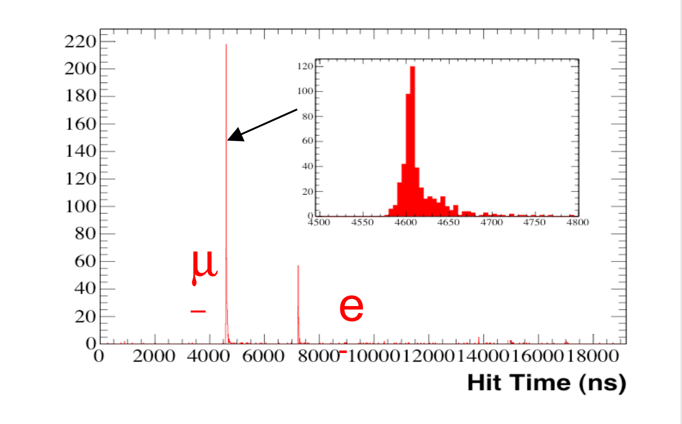
$$\nu_\mu + N \rightarrow \mu^- + N + \pi^+$$
$$\quad\quad\quad \rightarrow \mu^+ \rightarrow \nu_\mu + \nu_e + e^+ \quad (\tau\sim2\mu s)$$
$$\quad\quad\quad\quad\quad \rightarrow \nu_\mu + \nu_e + e^- \quad (\tau\sim2\mu s)$$

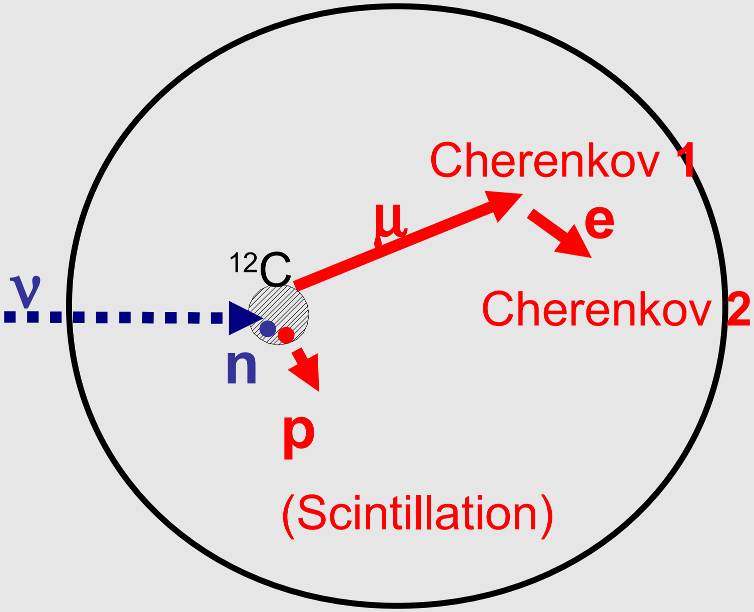
- CCπ^+ is (largest) background,
  (e^{+-} missed because of π absorption, μ^- capture)

- Important detail:
  - MiniBooNE data used to measure this background
  - ~1/2 of CCπ background is “irreducible” or “CCQE-like” (no π in final state)

Final CCQE sample:
- 146k CCQE candidates
- 27% efficiency
- 77% purity

evt time dist in (19μs) DAQ window





T, Katori, Ph.D, Indiana U
PRD 81, 092005 (2010),
PRL 100, 032301 (2008)

MiniBooNE CCQE analysis

- At this stage, fit (shape-only) for M_A, κ
  (but, not main result of analysis and has no effect on cross section results).

  M_A^{eff} = 1.35 ± 0.17 GeV (stat+sys)
  κ = 1.007± 0.007(stat+sys)
  χ^2/ndf = 47.0/38

- Compared to prev result, best fit values change somewhat with new background (CCπ) measurement and subtraction.

- data compared to world-average M_A and κ = 1.0 (no PB correction):

  χ^2/ndf = 67.5/40 (0.5% prob)

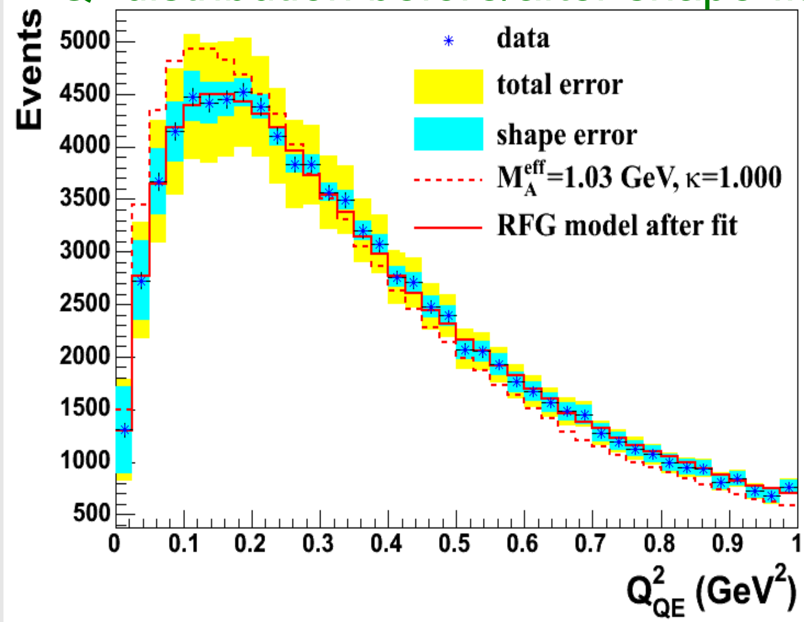
- M_A^{eff} only fit:

M_A^{eff} = 1.37 ± 0.12 GeV , χ^2/ndf = 48.6/39

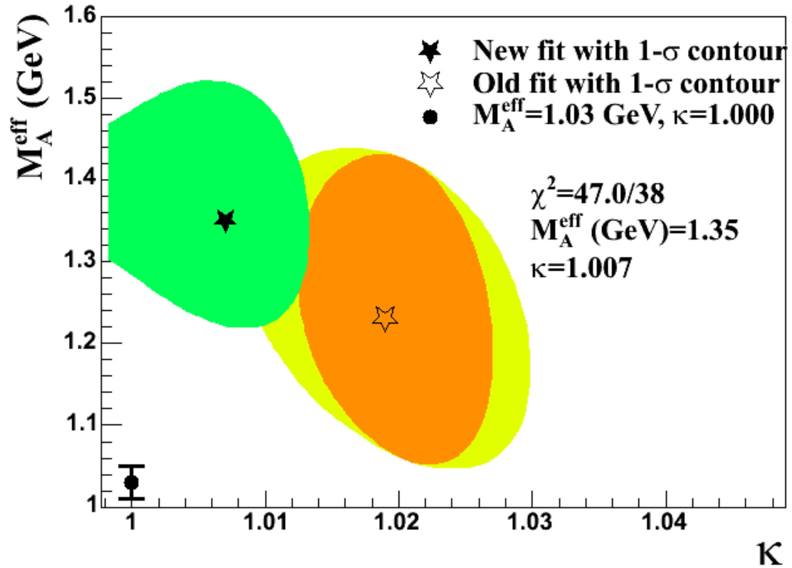
These fit parameters can now be used within MB RFG model for good description of data (modulo possible cross section normalization factors).

... then on to cross section extraction...

Q^2 distribution before/after shape-fit



M_A^{eff} - κ shape-only fit result



PRD 81, 092005 (2010)

MiniBooNE CCQE results

Double-differential cross section:

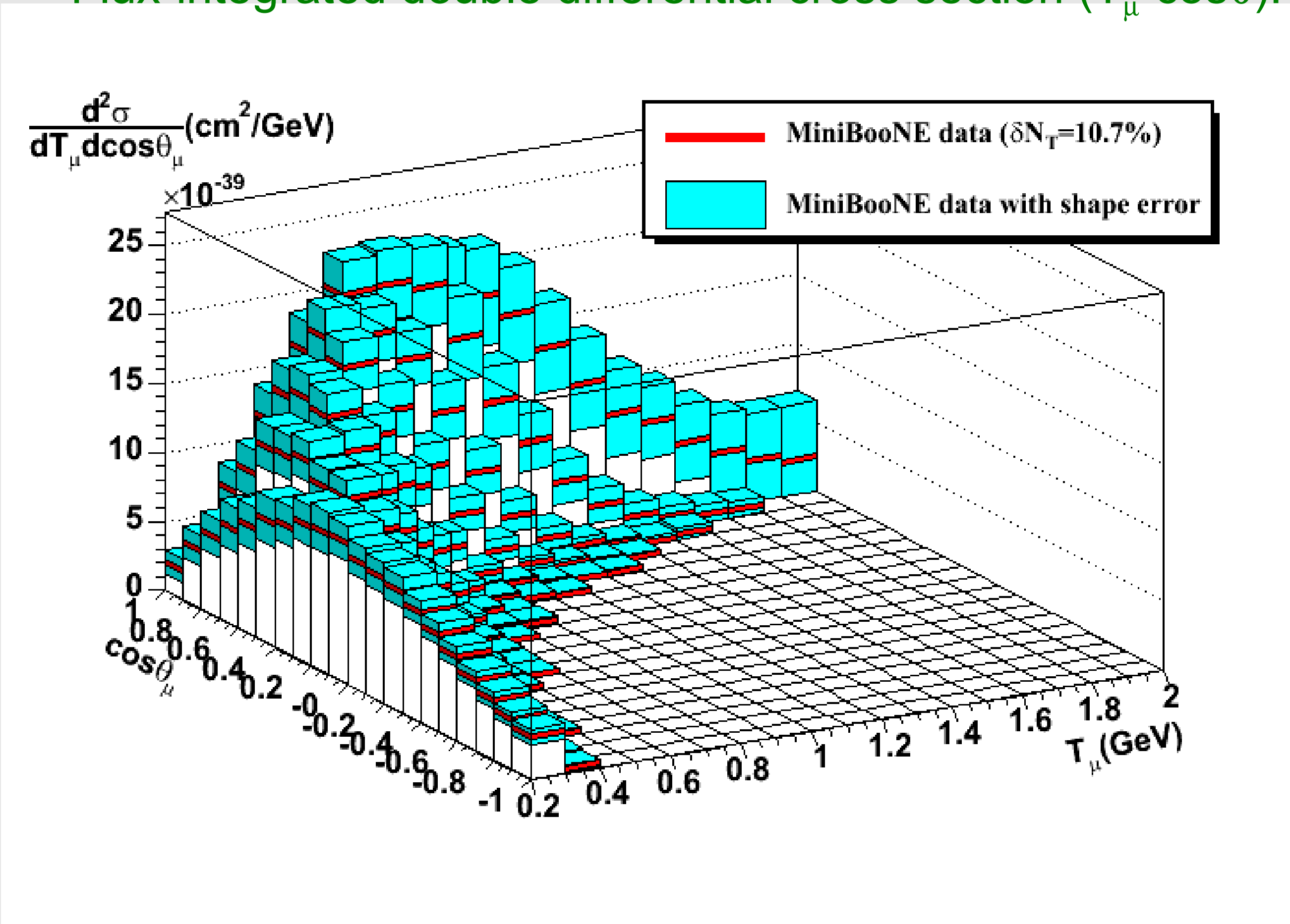
- Maximum information measurable on CCQE process from MB (which uses muon only)

- Most model-independent result possible

- normalization (scale) error is 10.7% (not shown)

- error bars show remaining (shape) error

Flux-integrated double differential cross section (T_μ-cosθ):



PRD 81, 092005 (2010)

MiniBooNE CCQE results

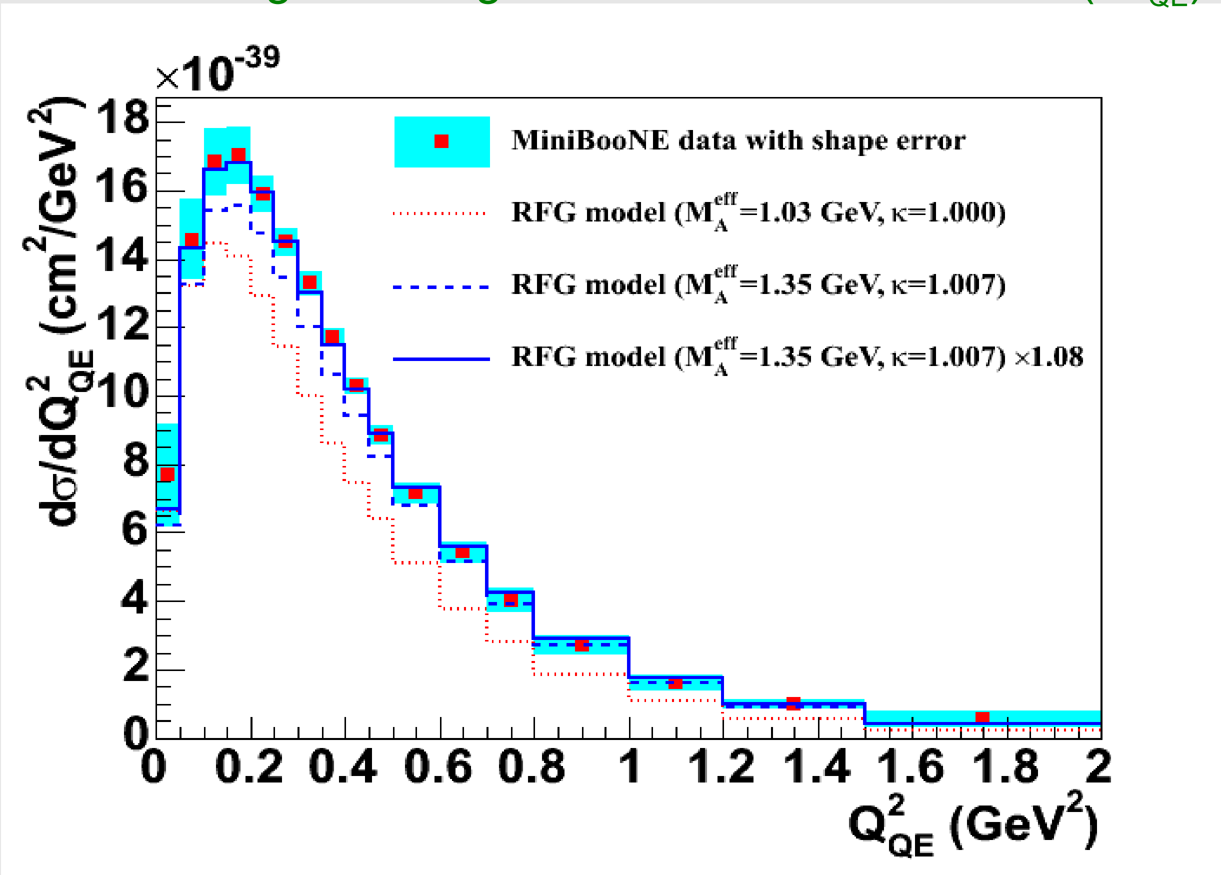
Single-differential
cross section:

- data is compared (absolutely) with CCQE (RFG) model with various parameter values

- Compared to the world-averaged CCQE model (red), MB CCQE data is 30% high

- RFG model with MB CCQE parameters (extracted from *shape-only* fit) agrees well with data over to within normalization error.

Flux-integrated single differential cross section (Q^2_{QE}):



PRD 81, 092005 (2010)

MiniBooNE CCQE results

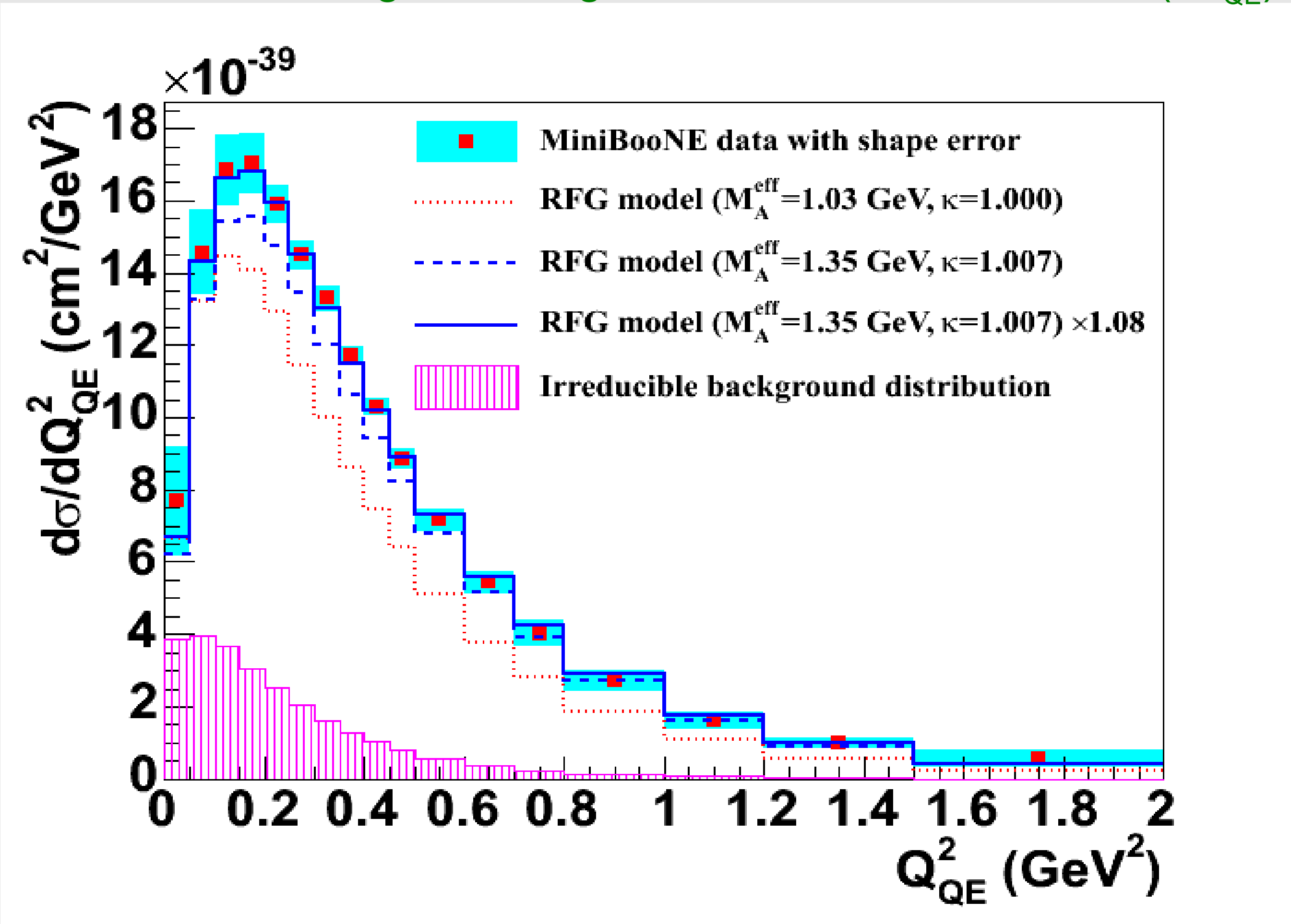
Single-differential cross section (again):

- same plot as previous but with "irreducible" (CCπ with π intra-nuc absorption) background shown.

- this background is subtracted, but may be undone (if desired) to produce "CCQE-like" sample

- also reported for double-diff xsection

Flux-integrated single differential cross section (Q^2_{QE}):



PRD 81, 092005 (2010)

MiniBooNE CCQE results

Total cross section:

- Total cross section is extracted by binning in "true" neutrino energy bins.
"$E_\nu^{QE,RFG}$"

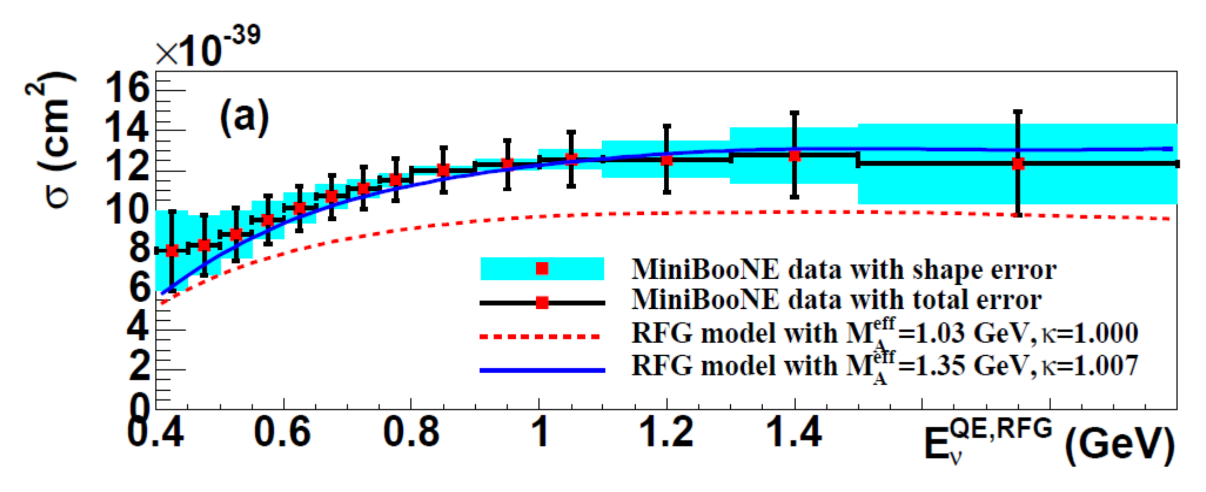
- Caution, model dependent, but conventional. -Opinion: better way to report is $d\sigma/dE_\nu^{QE}$

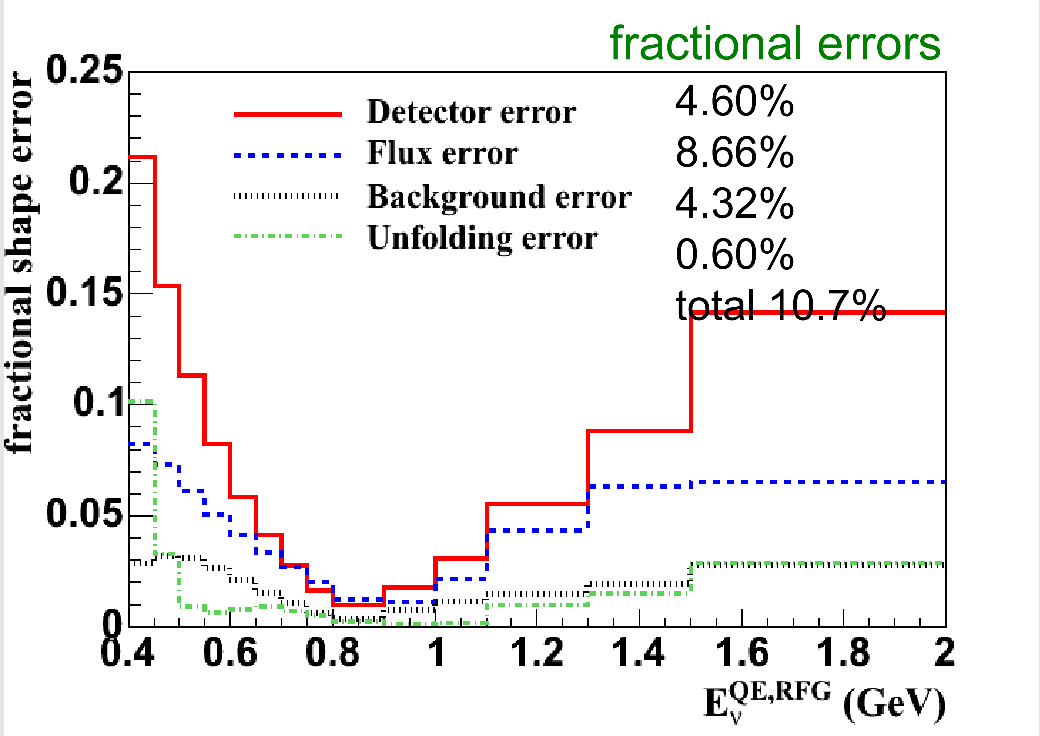
- Again, total cross section value well-reproduced from extracted CCQE model parameters

- Fractional errors (as function of neutrino energy) and overall normalization errors reported

- Note how frac errors grow "off-peak" of flux. Important to consider for extracting energy-dependence

Flux-unfolded total cross section ($E_\nu^{QE,RFG}$)





MiniBooNE CCQE results

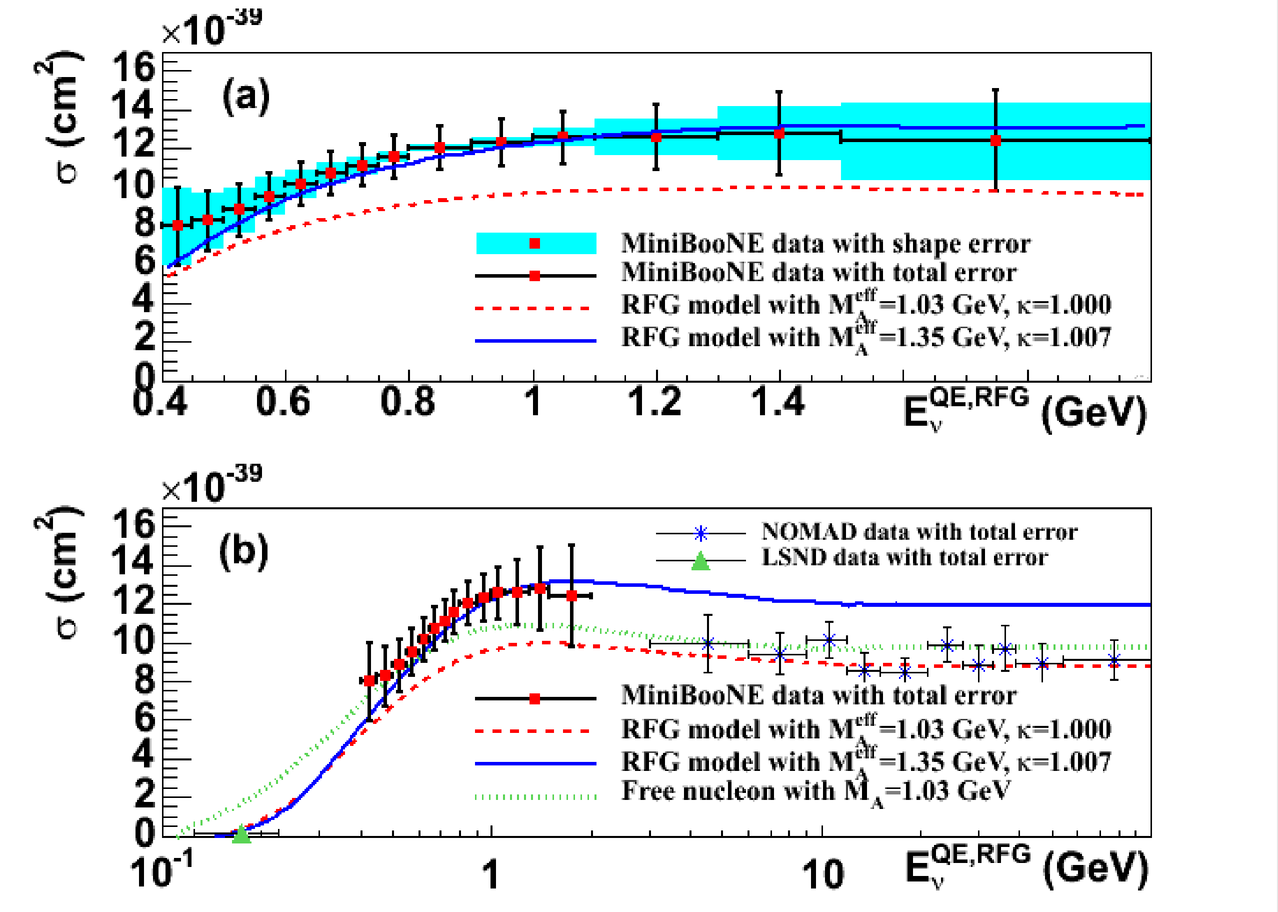
MiniBooNE CCQE total cross section:

- ~30% larger than expected with world-average M_A

- ~10% larger than free-nuc (world-average M_A) value

- However, M_A~1.35 GeV descibes data in both Q^2 shape and total cross section (within RFG model), coincidence?

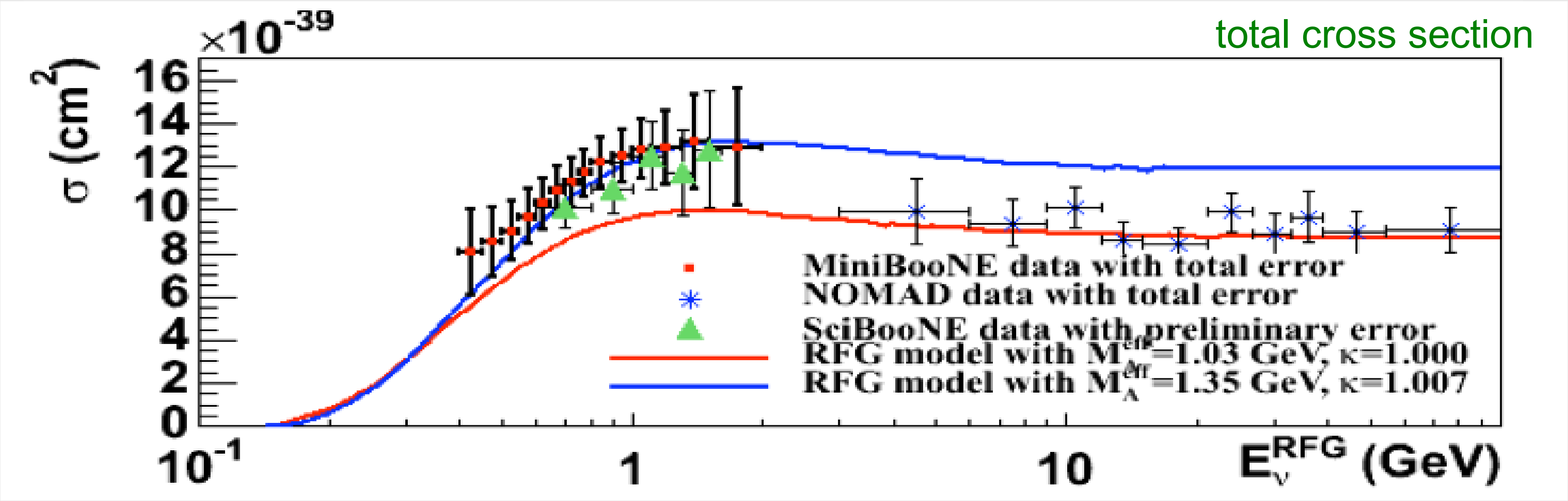
Flux-unfolded total cross section ($E_\nu^{QE,RFG}$)



PRD 81, 092005 (2010)

MiniBooNE CCQE results

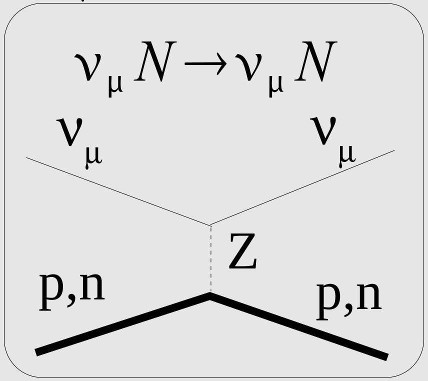
- MB results are consistent with SciBooNE, a highly segmented scibar in Booster ν beam at FNAL (as MiniBooNE) (arXiv:0909.5647)



- NOMAD:
  - wire chamber detector at CERN, mostly carbon target, 3-100 GeV
  - in agreement with "world-average" M_A , M_A=1.05±0.02±0.06 GeV
  - EPJ C63, 355 (2009)
- MINOS:
  - Fe target, ~5GeV
  - yields larger M_A (1.2 ± 0.1 ± 0.1 GeV) consistent with MiniBooNE, SciBooNE, K2K
  - AIP Conf. Proc. 1189, 133 (2009)

ν NC elastic scattering from MiniBooNE

ν_μ NC elastic



- The most fundamental NC probe of the nucleus/nucleon.

- Does our knowledge of CCQE (usually measured via muon) completely predict NCel (measured via recoil nucleon) for nuclear targets?

- Unlike CC quasielastic, sensitive to isoscalar component of nucleon (strange quarks) via isoscalar or "strange" axial-vector formfactor, $G_A^s(Q^2)$ and $\Delta s = G_A^s(Q^2 = 0)$

axial nucleon weak neutral current

$$\langle N|A_\mu^Z|N\rangle = -\left[\frac{G_F}{\sqrt{2}}\right]^{1/2} \langle N|\frac{1}{2}\{\underbrace{\bar{u}\gamma_\mu\gamma_5 u}_{\Delta u} - \underbrace{\bar{d}\gamma_\mu\gamma_5 d}_{\Delta d} - \underbrace{\bar{s}\gamma_\mu\gamma_5 s}_{\Delta s}\}|N\rangle$$

$$= -\left[\frac{G_F}{\sqrt{2}}\right]^{1/2} \langle N|\frac{1}{2}\{-G_A(Q^2)\gamma_\mu\gamma_5\tau_z + G_A^s(Q^2)\gamma_\mu\gamma_5\}|N\rangle$$

- Experimental sensitivity to isoscalar effects best via ratios:

  - NC(p)/NC(n), NC(p)/NC(p+n), NC(p)/CCQE

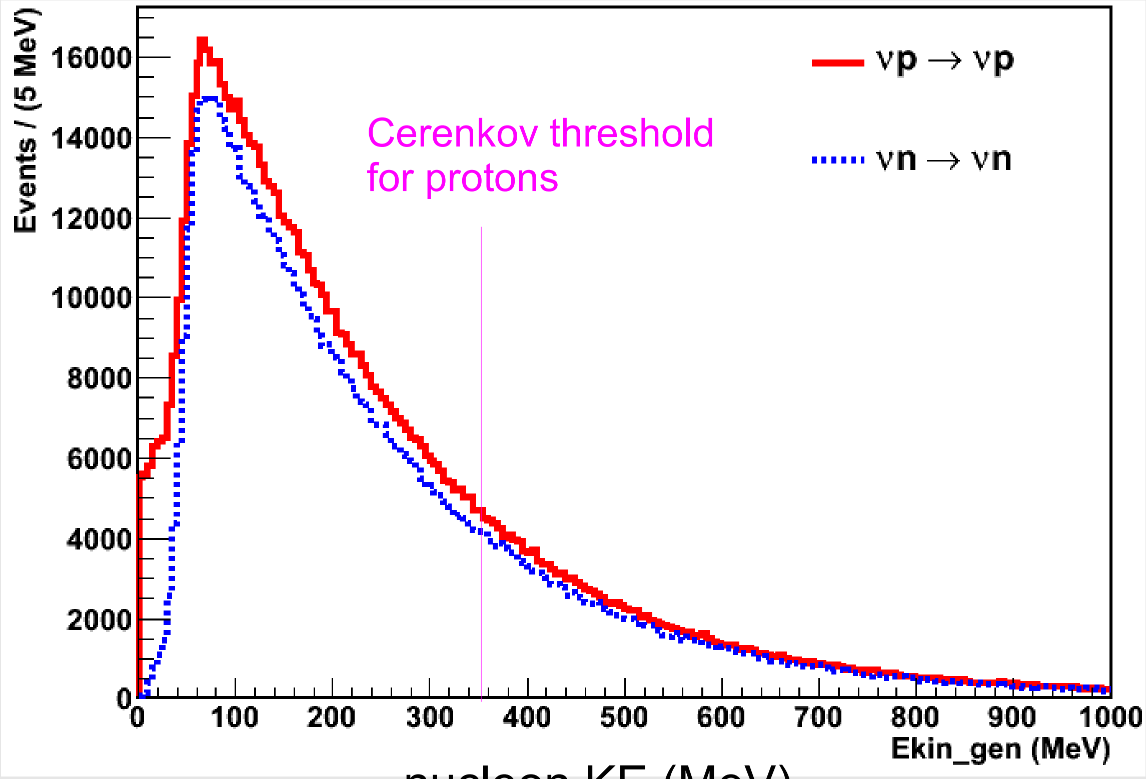
as many systematics (flux, nuc. effects) should cancel.
Requires separation of protons/neutrons.

MiniBooNE NC elastic analysis

- NCel experimental definition: 1 p/n , no μ^- , π

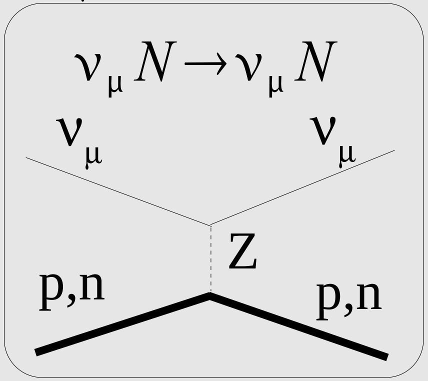
- below Cerenkov threshold, p/n separation not possible, p/n recon'd via small amount of scintillation

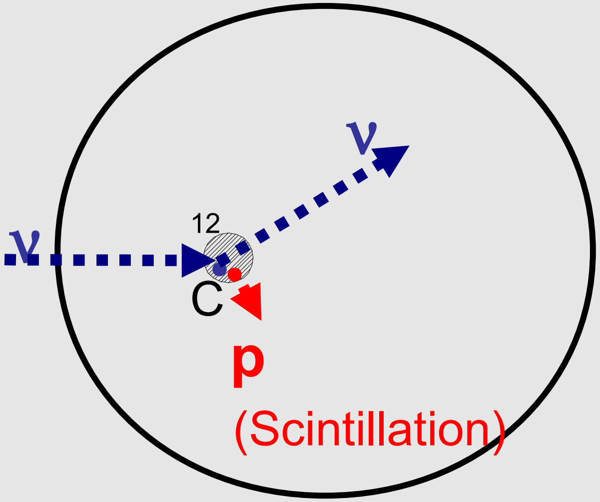
MC NCel event distribution



nucleon KE (MeV)

ν_μ NC elastic





D. Perevalov, Ph.D, Alabama U.
Phys. Rev. D82, 092005 (2010)

MiniBooNE NC elastic analysis

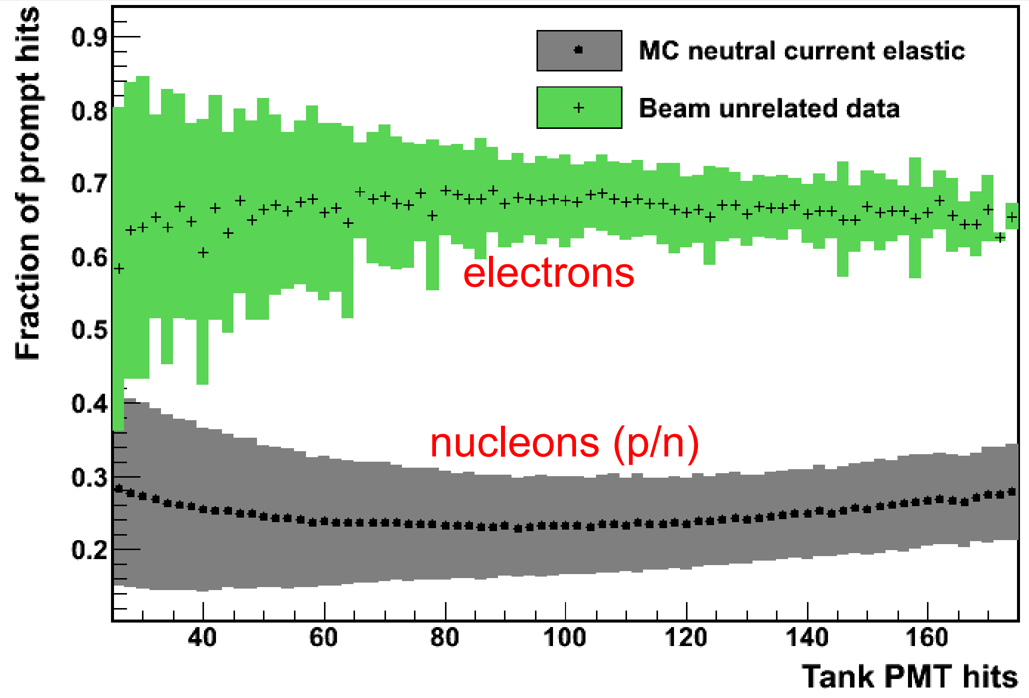
- requires dedicated reconstruction for protons (new to this analysis)

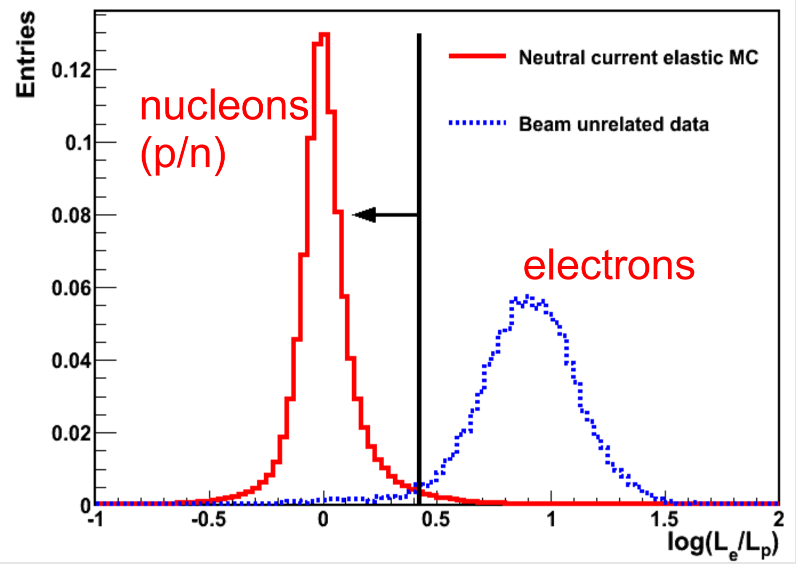
- proton fitter provides good separation between nucleons/electrons

- NCel sample:
  - 94.5K candidate evts
  - efficiency = 26%
  - purity = 65%

- NC$\pi^{+/-}$ is (largest) background, (π^{+-} missed because of π absorption)

- ~1/3 of background is NCel-like





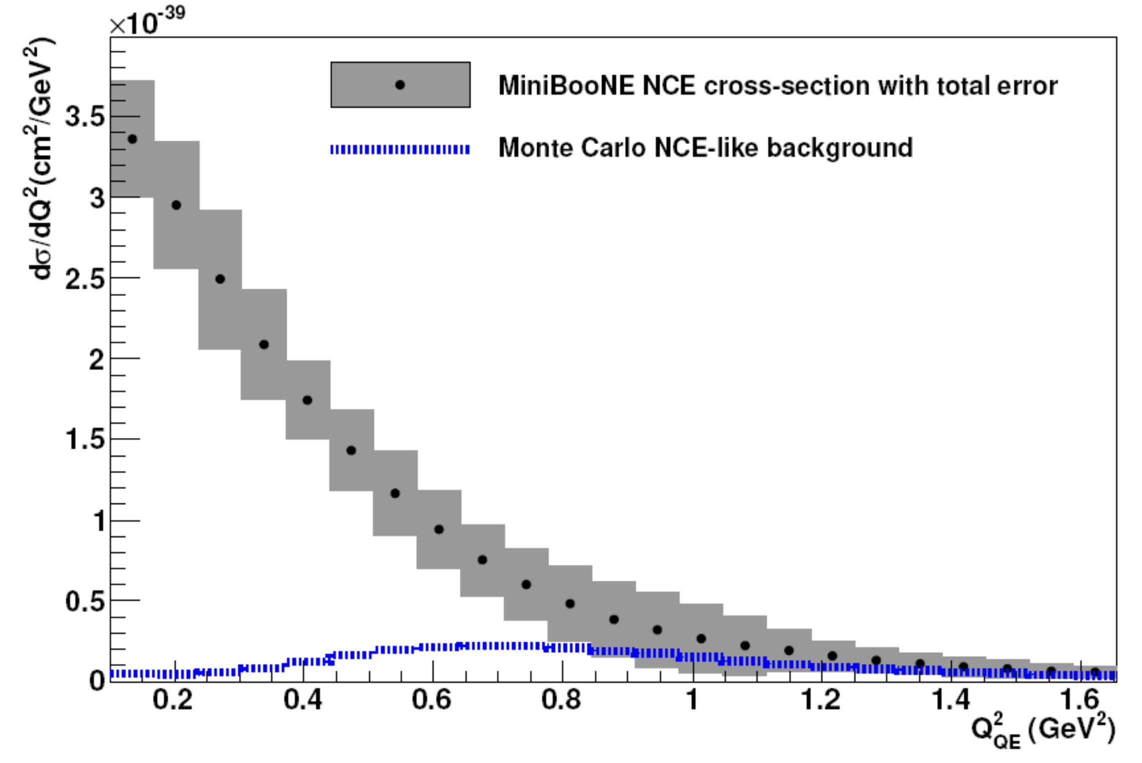
MiniBooNE NC elastic results

- differential cross section:

- actually the wtd sum of 3 different processes:

$$\frac{d\sigma_{\nu N\to\nu N}}{dQ^2} = \frac{1}{7}C_{\nu p,H}(Q^2)\frac{d\sigma_{\nu p\to\nu p,H}}{dQ^2} + \frac{3}{7}C_{\nu p,C}(Q^2)\frac{d\sigma_{\nu p\to\nu p,C}}{dQ^2} + \frac{3}{7}C_{\nu n,C}(Q^2)\frac{d\sigma_{\nu n\to\nu n,C}}{dQ^2},$$

NCel differential cross section



- ~1/3 of background is NCel-like (NCπ with π abs). This calc'd background is reported so NCel-like may be calculated.

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MiniBooNE NC elastic results

- M_A extraction:

- from an absolute fit to proton KE distribution

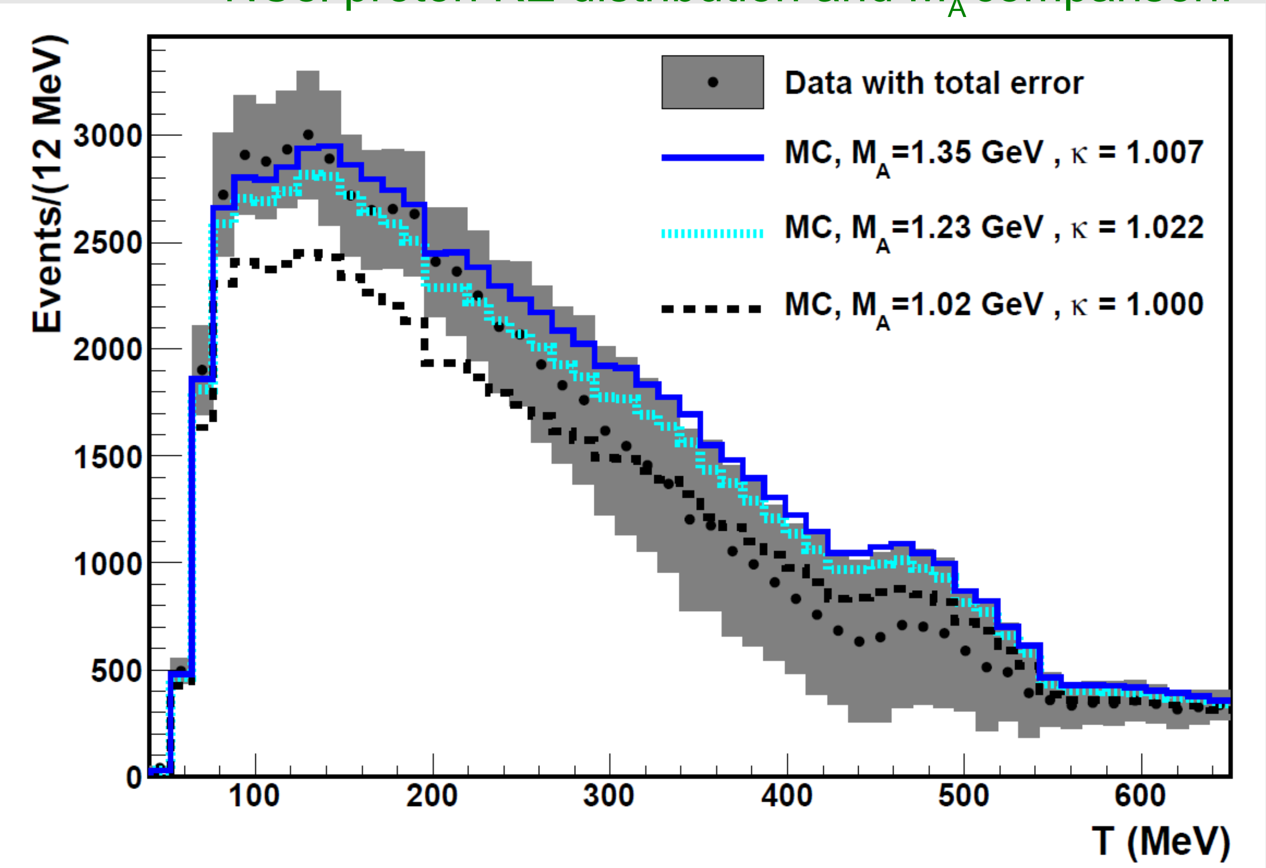
M_A = 1.39 ± 0.11 GeV
χ^2/ndf = 26.9/50

- small sensitivity to Δs, assume Δs = 0.

- negligible sensitivity to κ

- consistent with M_A from CCQE (shape) fit

NCel proton KE distribution and M_A comparison:



Phys. Rev. D82, 092005 (2010)

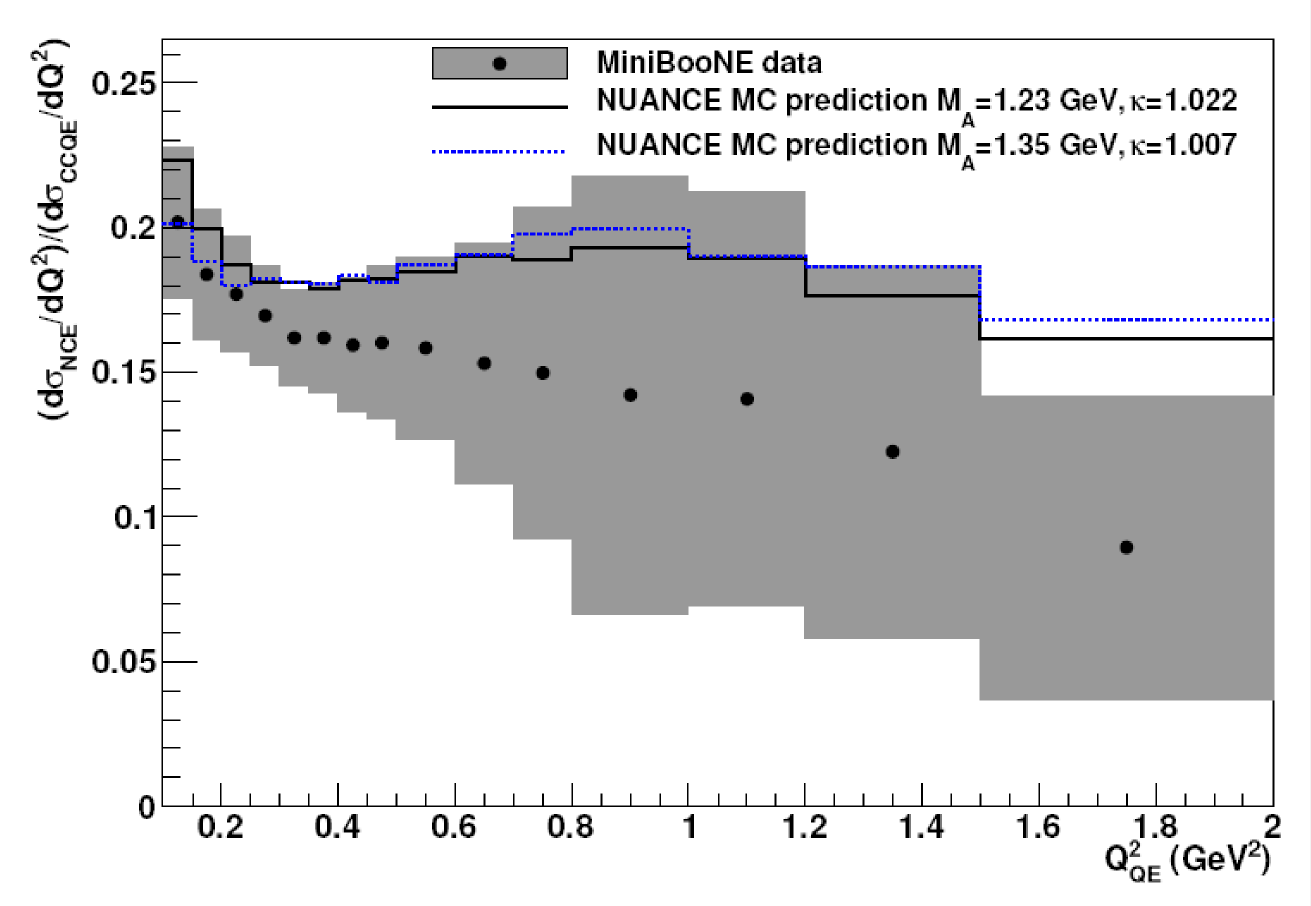
MiniBooNE NC elastic results

- NCel to CCQE differential cross section ratio:

- flux error cancels between the 2 channels

- ratio is consistent with our RFG model. So no discrepency in NCel compared to CCQE

NCel to CCQE differential cross section ratio



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MiniBooNE NC elastic results

- Δs extraction:

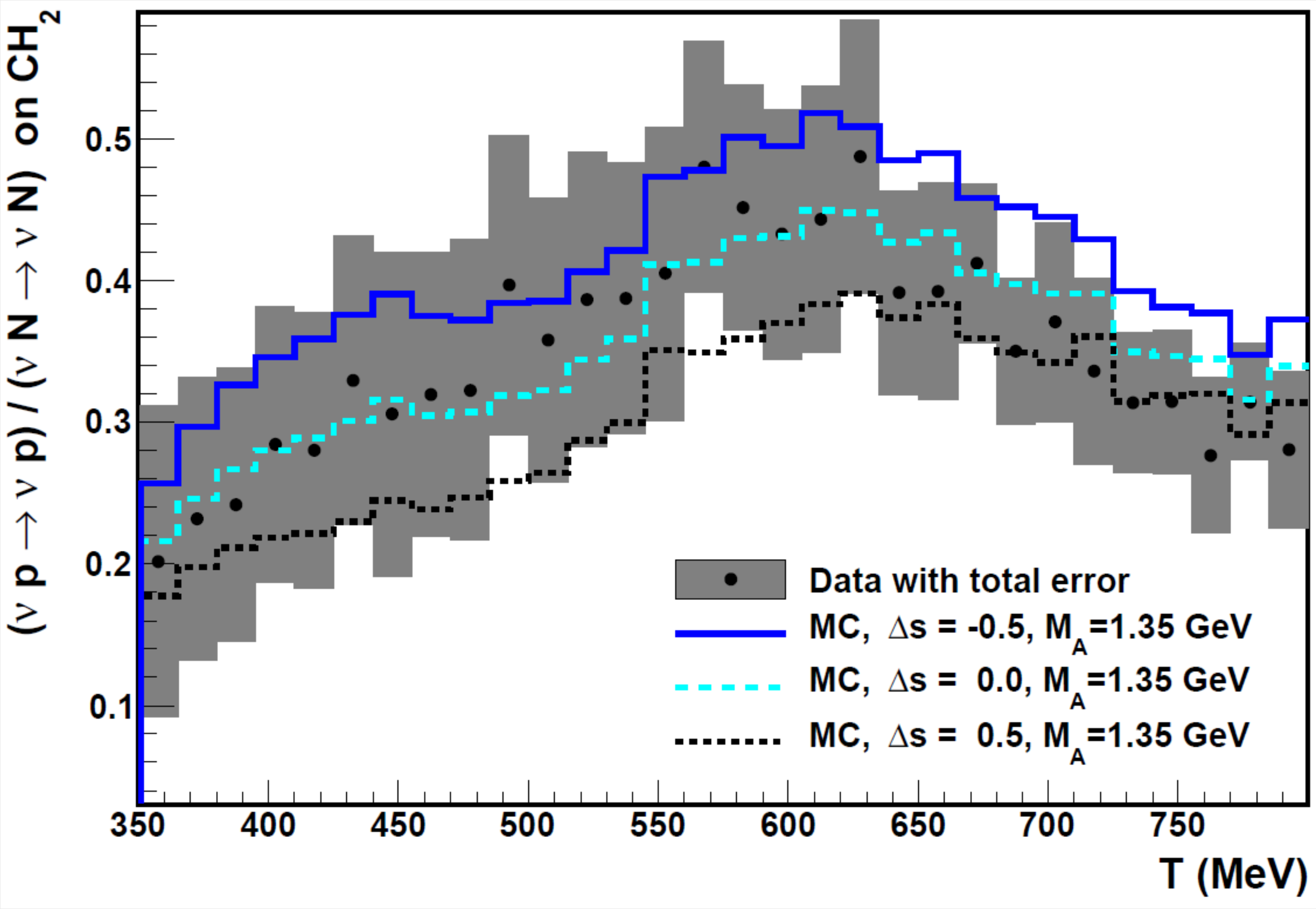
- from NC(p)/NC(p+n) above proton cerenkov threshold where proton separation is possible

- $\Delta s = 0.08 \pm 0.26$

- limited by large errors but good demo of method

- consistent with expectations from deep-inelastic scattering meas:

$\Delta s \sim -0.10$



Phys. Rev. D82, 092005 (2010)

CCπ production in MiniBooNE

– ν CC production of π^+, π^0
- background (and perhaps signal) for oscillations
- insight into models of neutrino pion production via nucleon resonances and via coherent production
- may also feed into "CCQE-like" events

$$\nu_\mu + p(n) \rightarrow \mu + \Delta^{+(+)} \rightarrow \mu + p(n) + \pi^+$$
$$\nu_\mu + A \rightarrow \mu + A + \pi^+$$

- CCπ^+/CCQE ratio measured in MiniBooNE

- CCπ^+/CCQE ratio in agreement with model.

- So CCπ^+ rate (cross section) is also larger than expected.

- In both FSI corrected/uncorrected samples

CCπ^+ /CCQE ratio, no FSI corrections

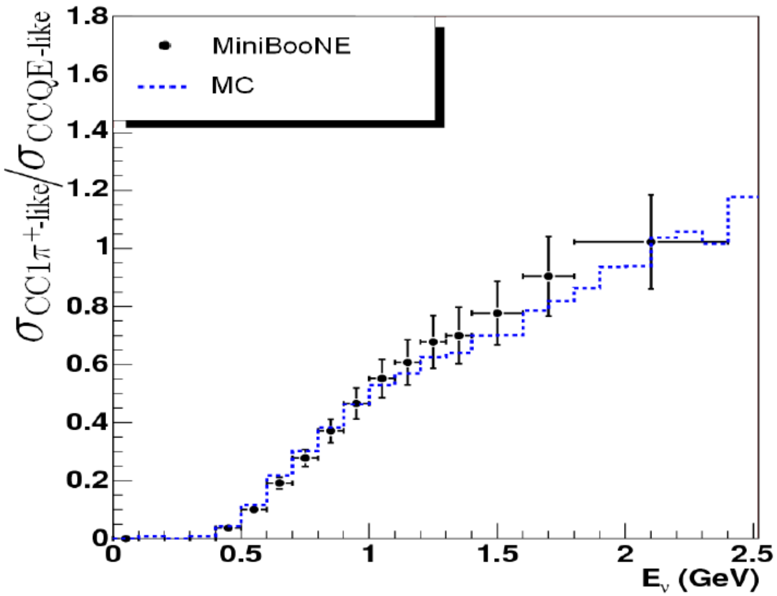


FIG. 1: Observed CC1π^+-like/CCQE-like cross section ratio on CH_2, including both statistical and systematic uncertainties, compared with the MC prediction [6]. The data have not been corrected for hadronic re-interactions.

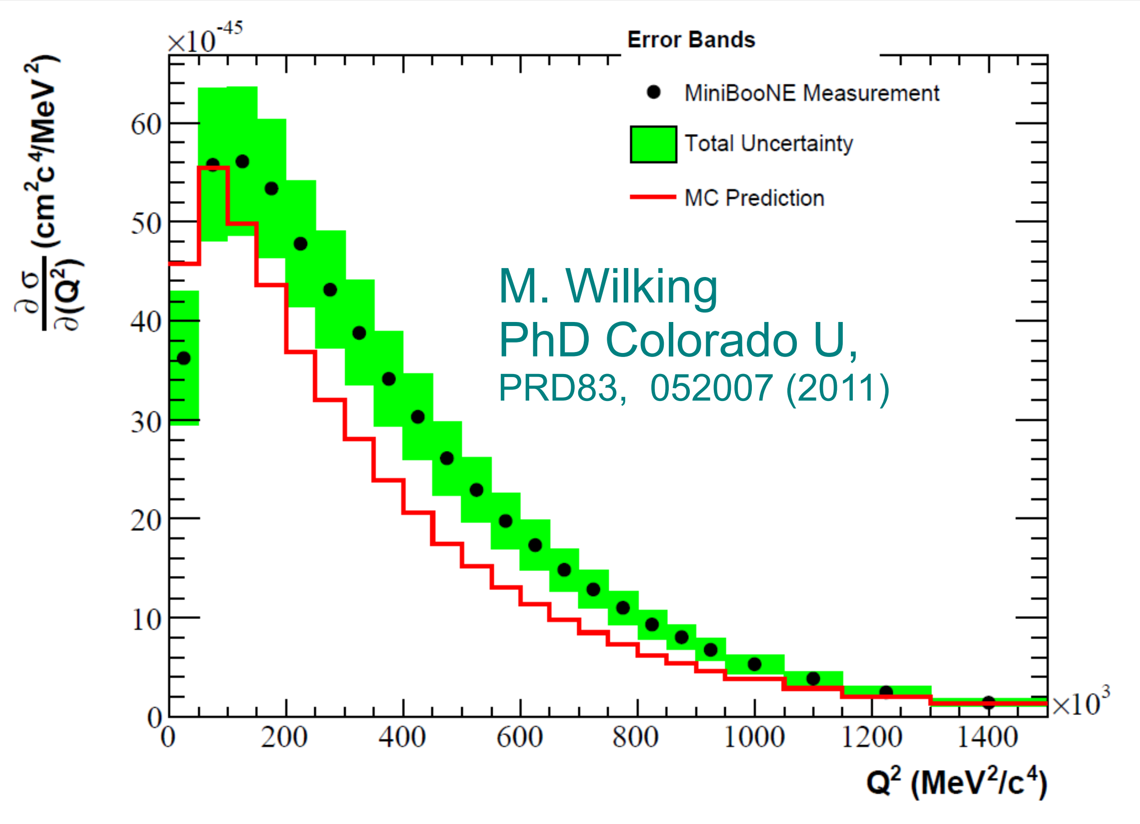
S. Linden, PhD, Yale
(Phys. Rev. Lett. 103, 081801 (2009))

CCπ production

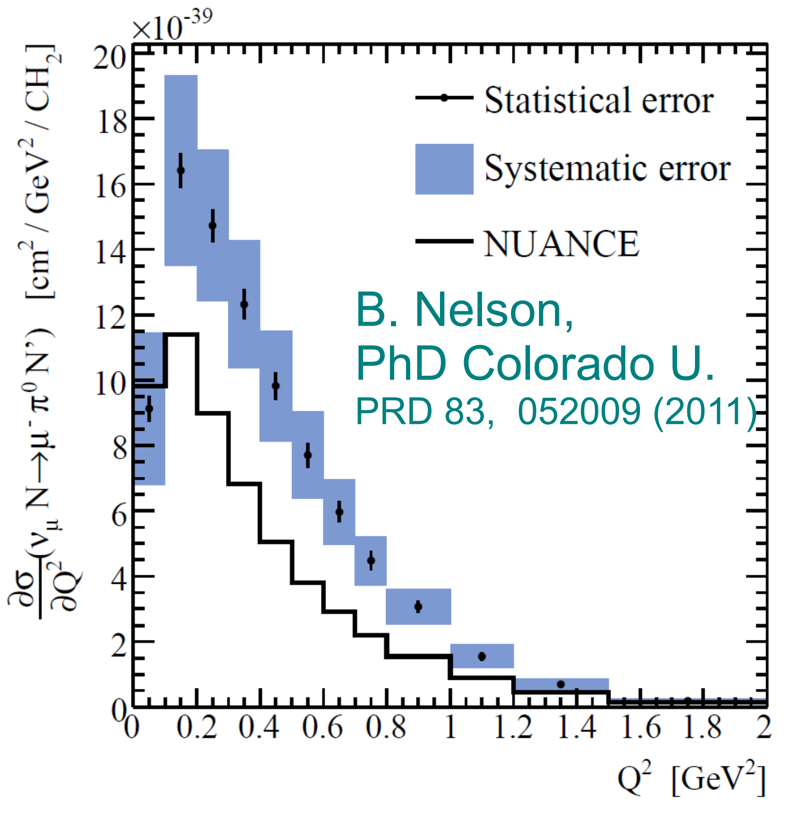
CCπ^+, π^0 differential cross sections from MiniBooNE:
- in a variety of kinematic variables
- model independent, absolutely norm'd
- will guide models of pion production including coherent piece
- excess of data over model present in these channels also.

$$\nu_\mu + p(n) \rightarrow \mu + \Delta^{+(+)} \rightarrow \mu + p(n) + \pi^+$$
$$\nu_\mu + A \rightarrow \mu + A + \pi^+$$

CCπ^+ differential cross sections



CCπ^0 differential cross section

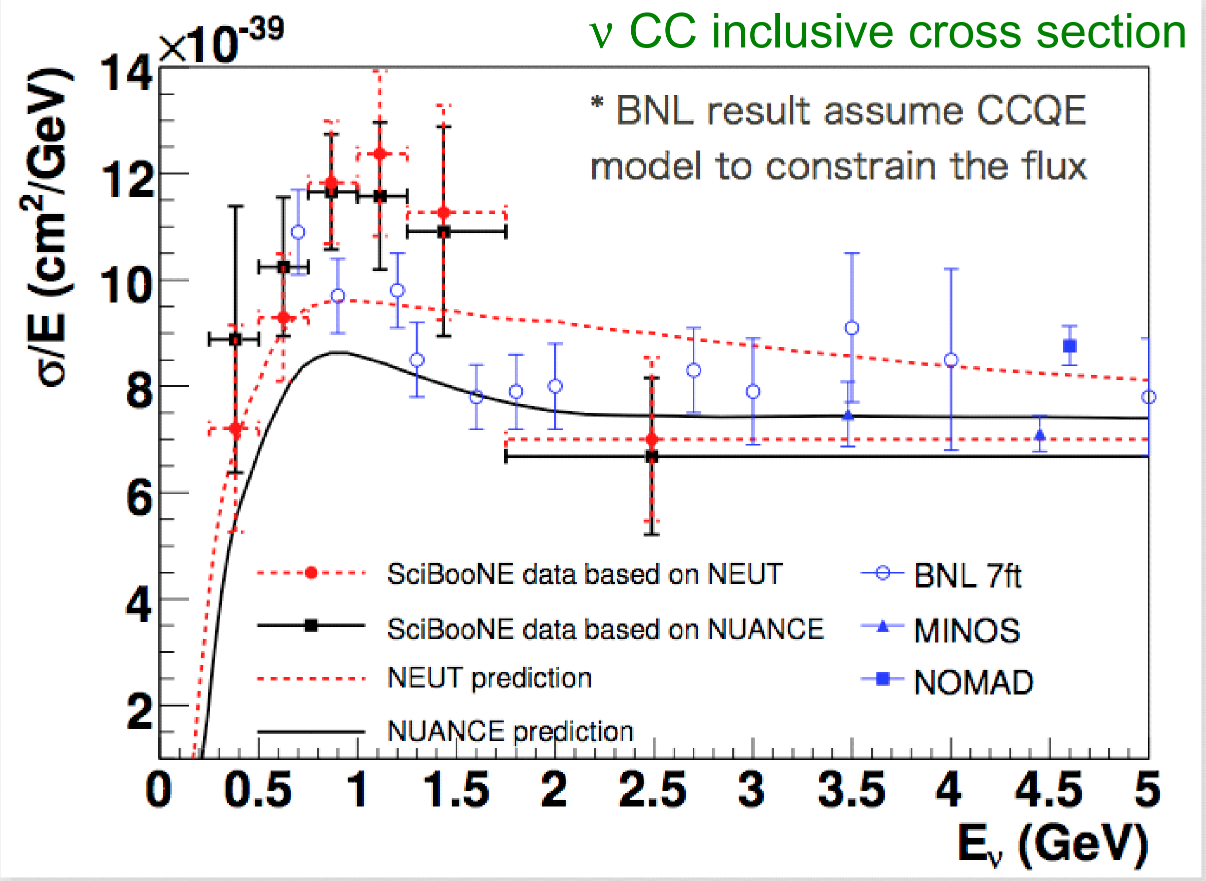


CC inclusive from MB

– ν CC inclusive scattering
  - should be understood together with exclusive channels
  - ~independent of final state details

- MB measurement coming soon

- recent SciBooNE result
(PRD 83, 012005, 2011)



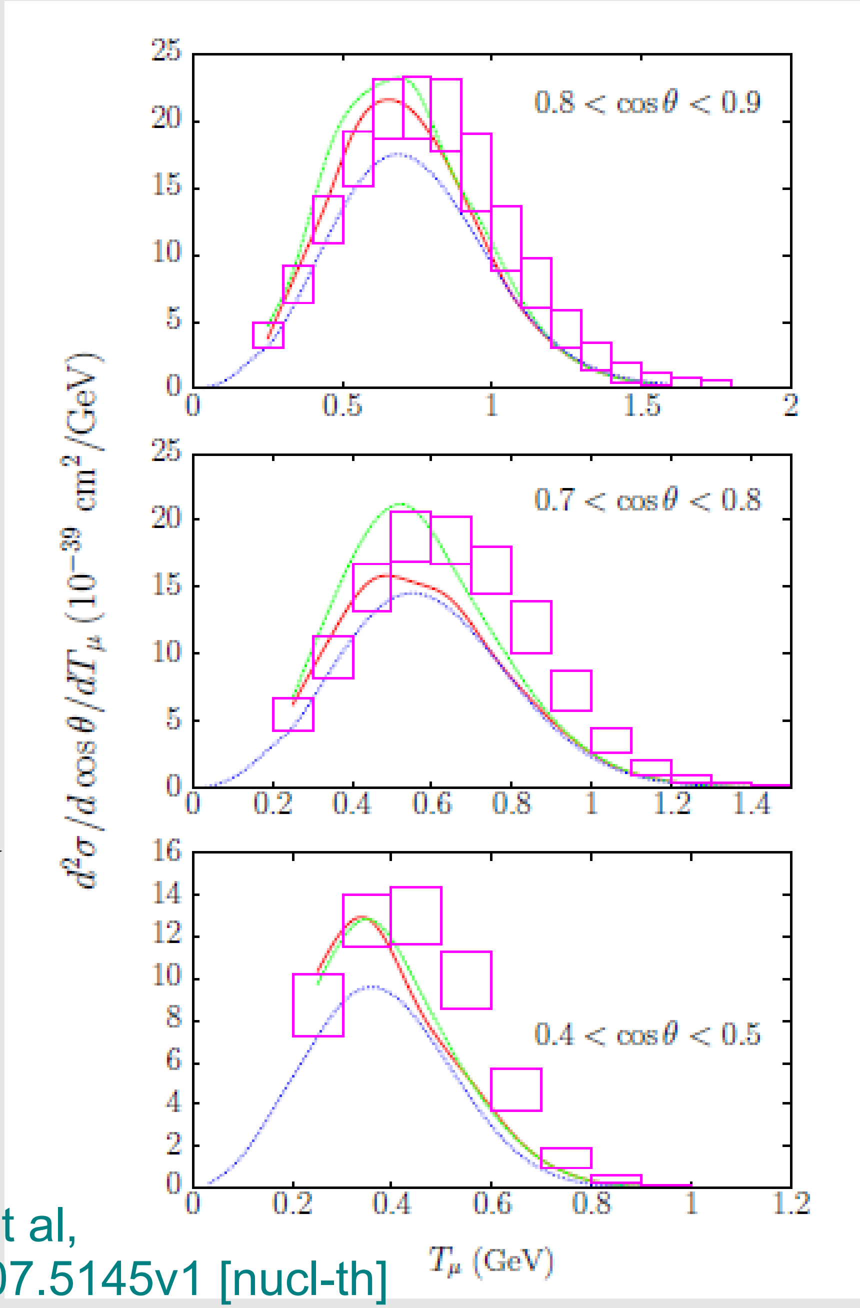
models for ν QE scattering

model comparison to MiniBooNE CCQE

Much theoretical interest in results recently:

Nieves et al., arXiv:1106.5374 [hep-ph]
Bodek et al., arXiv:1106.0340 [hep-ph]
Amaro, et al., arXiv:1104.5446 [nucl-th]
Antonov, et al., arXiv:1104.0125
Benhar, et al., arXiv:1103.0987 [nucl-th]
Meucci, et al., Phys. Rev. C83, 064614 (2011)
Ankowski, et al., Phys. Rev. C83, 054616 (2011)
Nieves, et al., Phys. Rev. C83, 045501 (2011)
Amaro, et al., arXiv:1012.4265 [hep-ex]
Alvarez-Ruso, arXiv:1012.3871[nucl-th]
Benhar, arXiv:1012.2032 [nucl-th]
Martinez, et al., Phys. Lett B697, 477 (2011)
Amaro, et al., Phys. Lett B696, 151 (2011)
Martini, et al., Phys. Rev C81, 045502 (2010)

- for example
comparisons to double diff xsection



Meucci et al,
arXiv:1107.5145v1 [nucl-th]

models for ν QE scattering

An interesting idea has emerged...

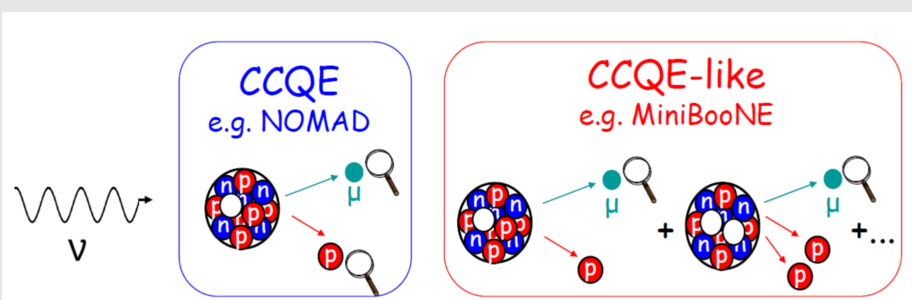
- Perhaps extra “strength” in CCQE from multi-nucleon correlations within carbon (Martini et al PRC80, 065501, '09)

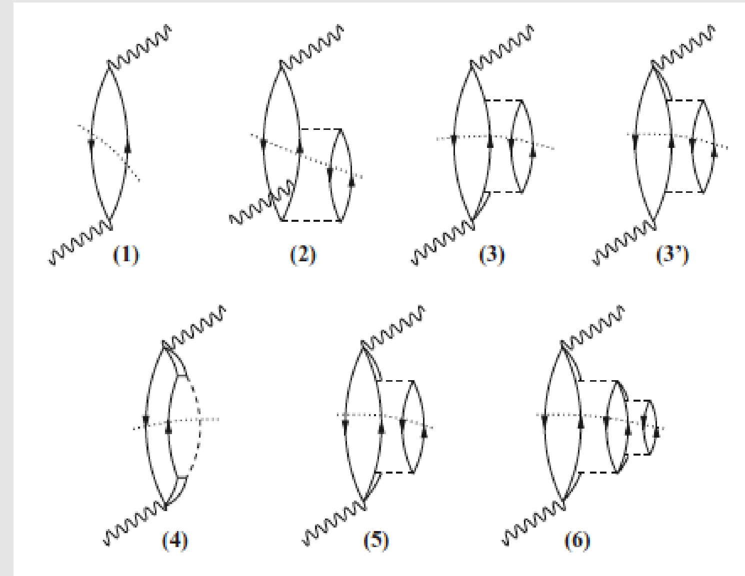
- Related to neglected “transverse” response in noted in electron scattering? (Carlson etal, PRC65, 024002, '02)

- Expected with nucleon correlations and 2-body exchange currents

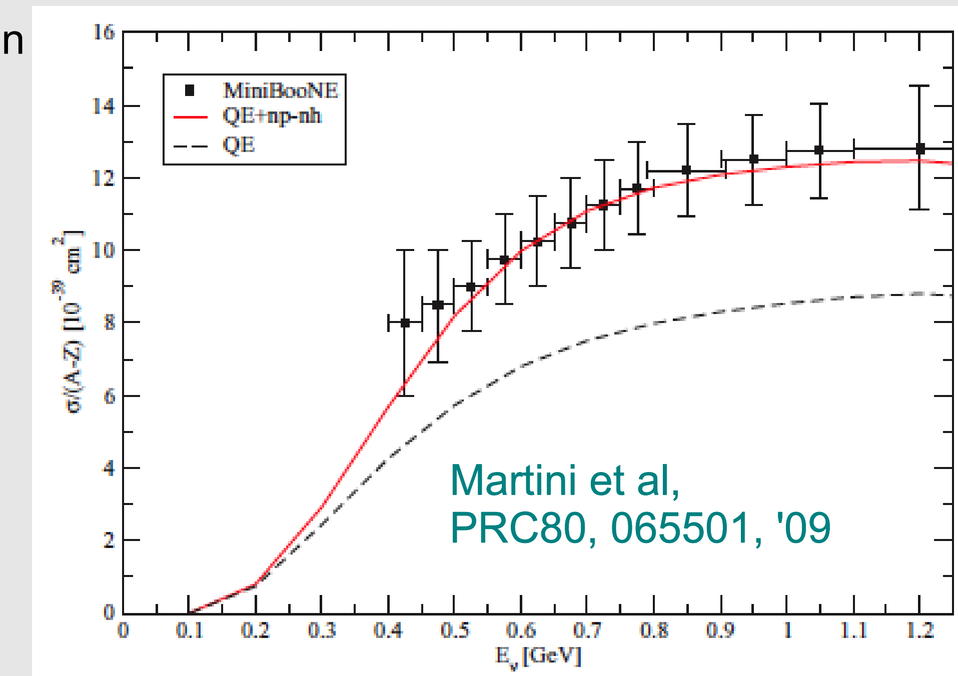
- Note: may effect neutrino energy reconstruction in oscillation experiments!

- Perhaps related to different CCQE selections, eg:



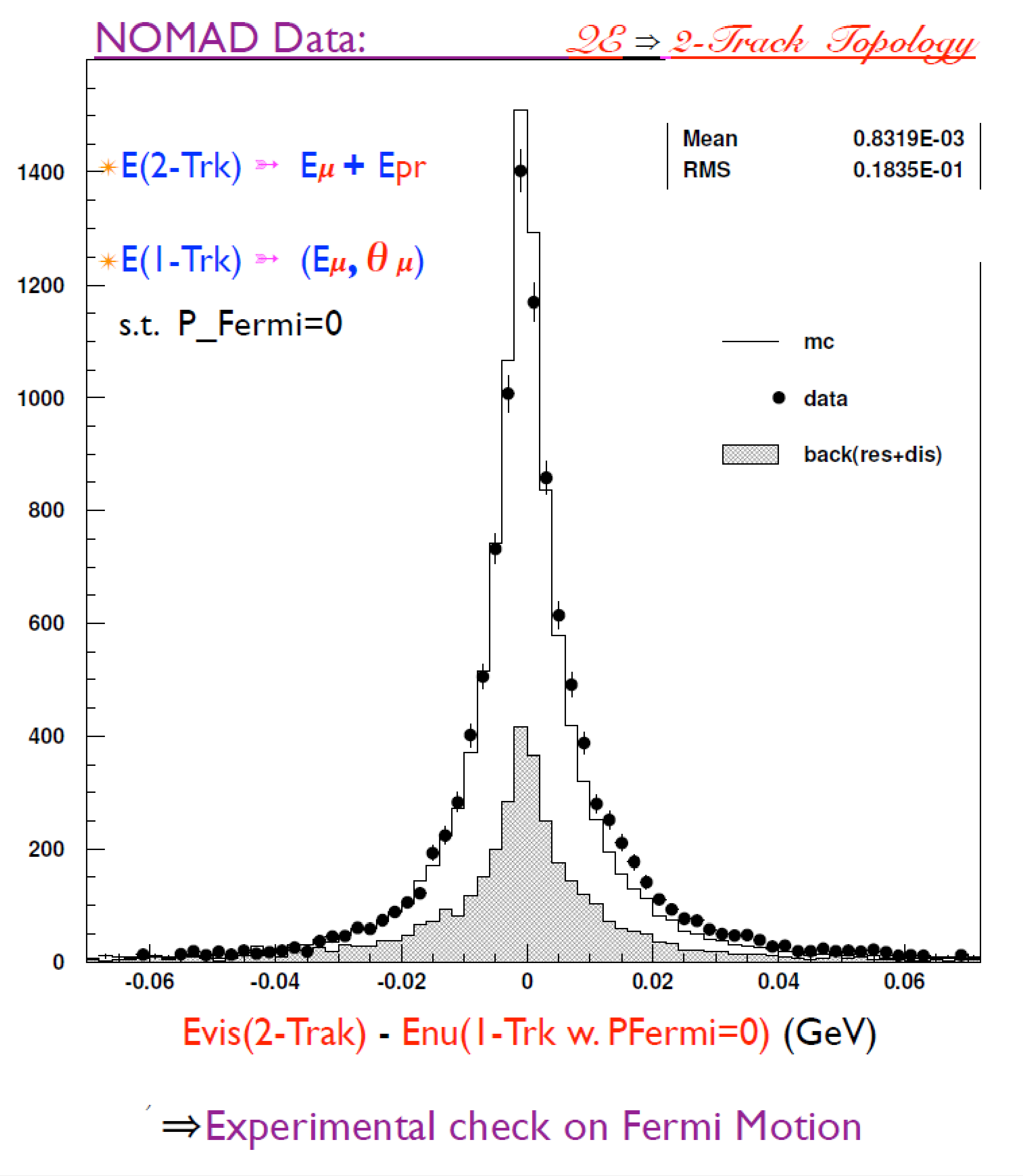


CCQE total cross section



models for ν QE scattering

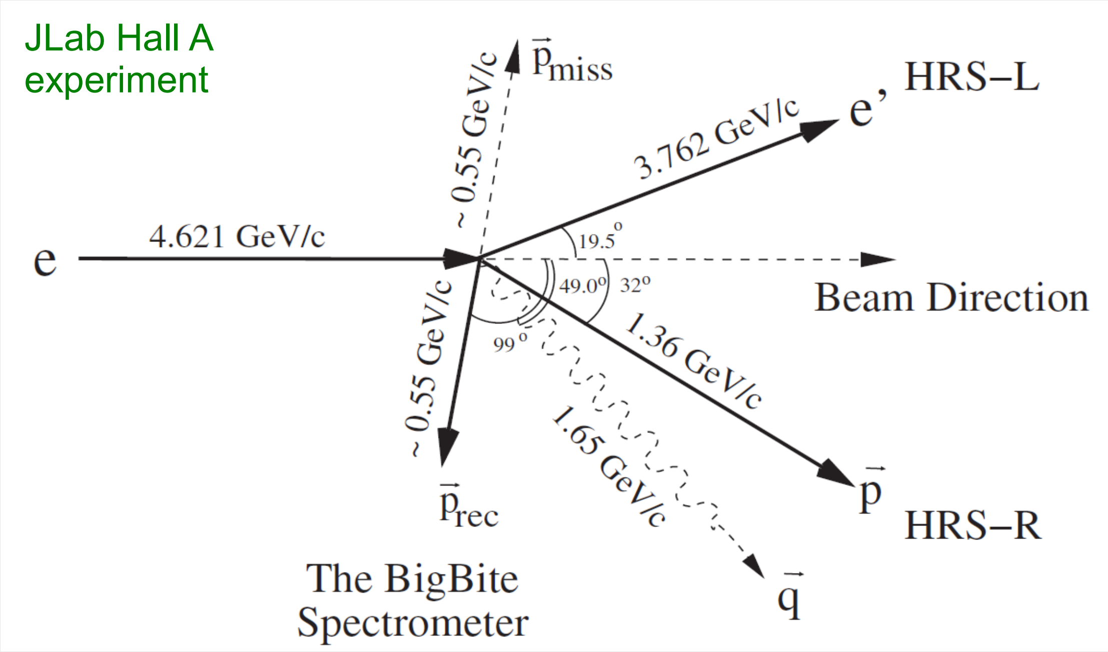
However, not clear that simple QE-selection argument can explain NOMAD-MiniBooNE differences.

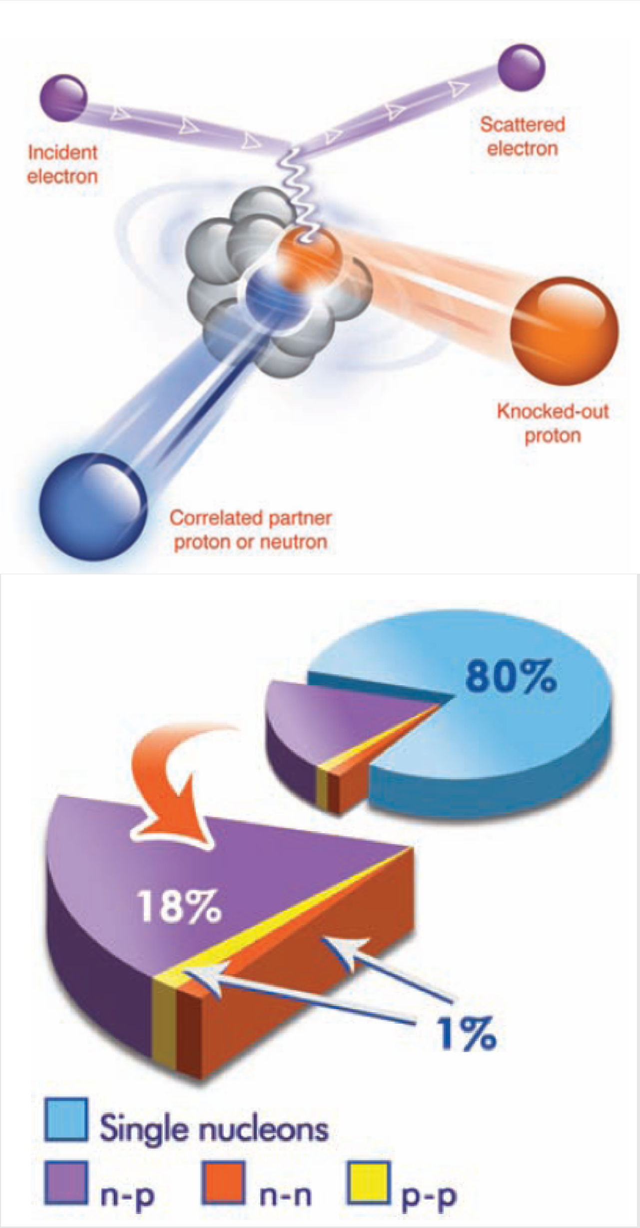


Courtesy:
S. Mishra

CCQE scattering and 2-N correlations

- Recent results from e-scattering suggest 20% of nucleons in carbon are in a "SRC state"
(R. Subedi etal, Science, 320, 1476 (2008))





- This effect should result in distinguishable final states of multiple recoil nucleons

- and have implications in interference terms (ν/ $\bar{\nu}$) differences

upcoming MB results: $\bar{\nu}$ CCQE

$\bar{\nu}$ calc diff xsection

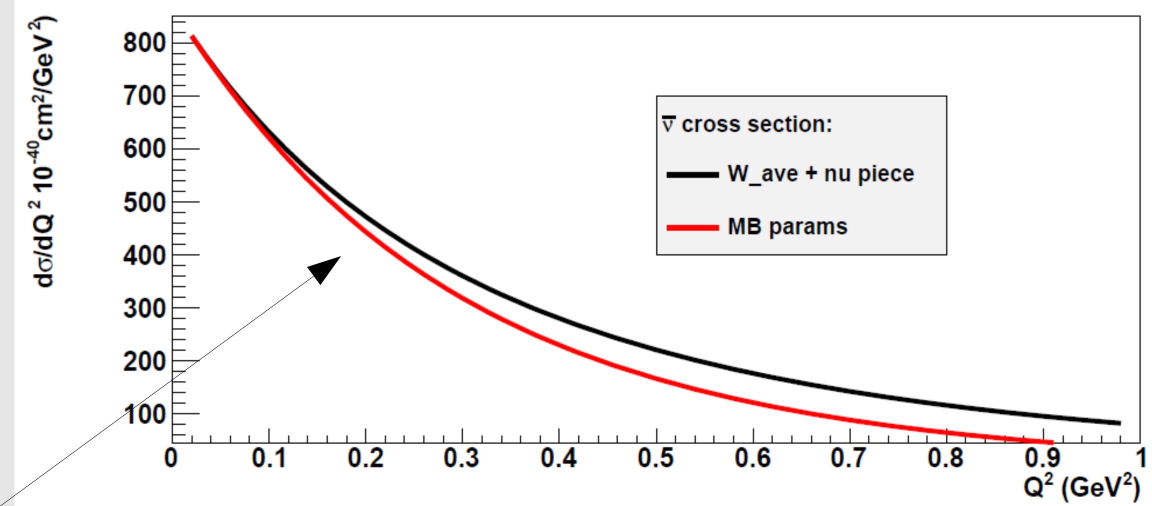
- If multinucleon correlations are large contribution in CC-"QE" scattering,
- should result in different final states,
- interference terms not as in 1N model
- and prediction for $\bar{\nu}$ CCQE based on ν data should show that.

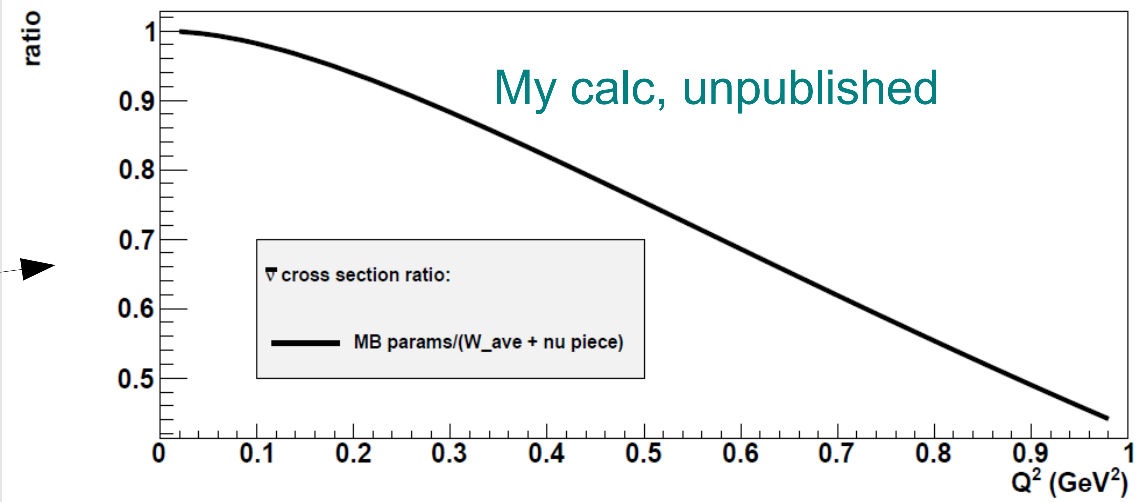
using simple L-S model:

– LS model with MB M_A

– LS with world ave M_A and extra (non-interfering) term

– ratio





L-S model:

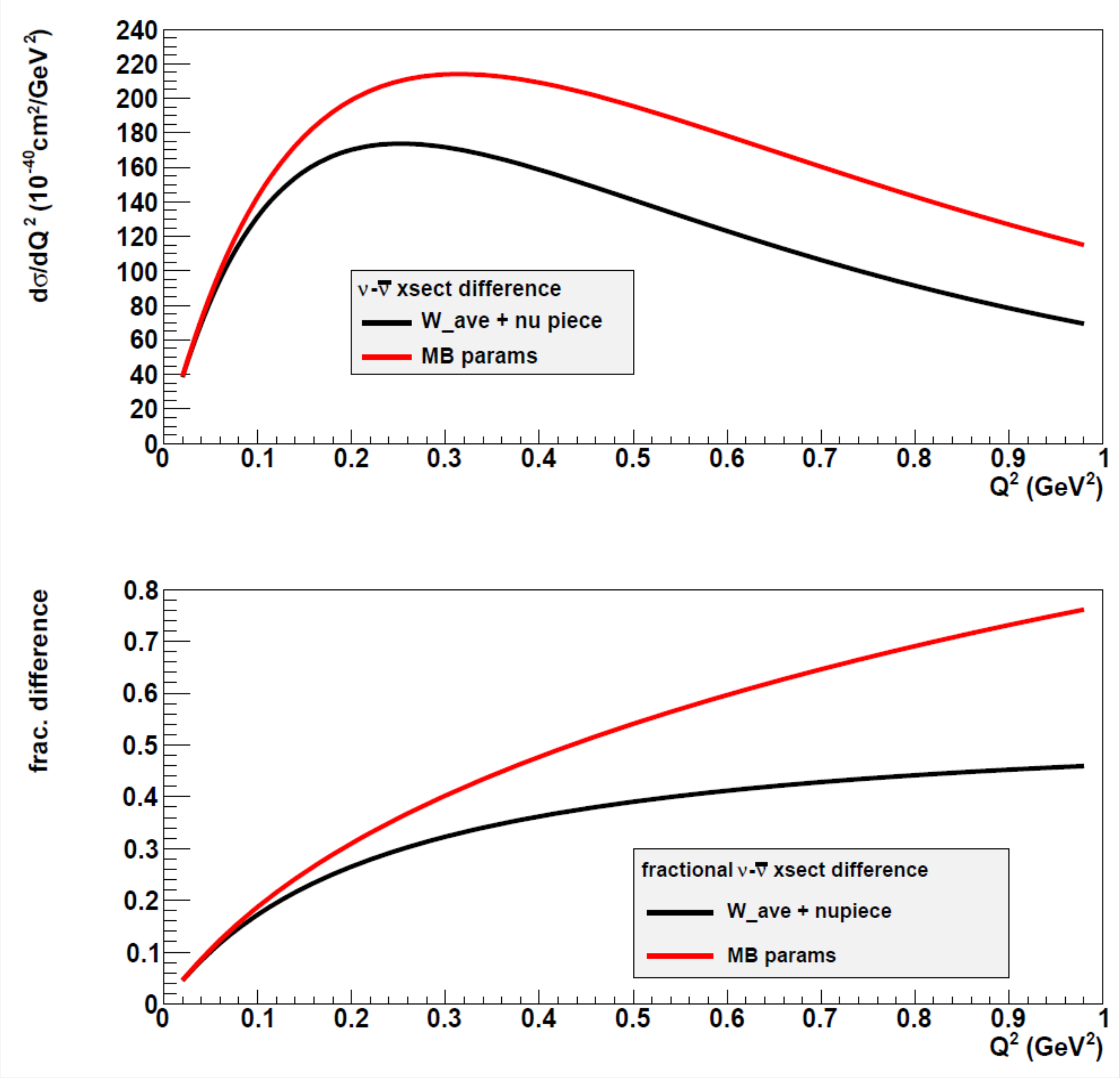
$$\frac{d\sigma}{dQ^2}\left(\begin{array}{c}\nu_l + n \rightarrow l^- + p \\ \bar{\nu}_l + p \rightarrow l^+ + n\end{array}\right) = \frac{M^2 G_F{}^2 cos^2\theta_c}{8\pi E_\nu{}^2}\left\{A(Q^2) \pm B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

upcoming MB results: $\bar{\nu}$ CCQE

Continuing with 2 different scenarios..

predicted $\nu - \bar{\nu}$ xsection diff:

predicted $\nu - \bar{\nu}$ xsection frac diff:



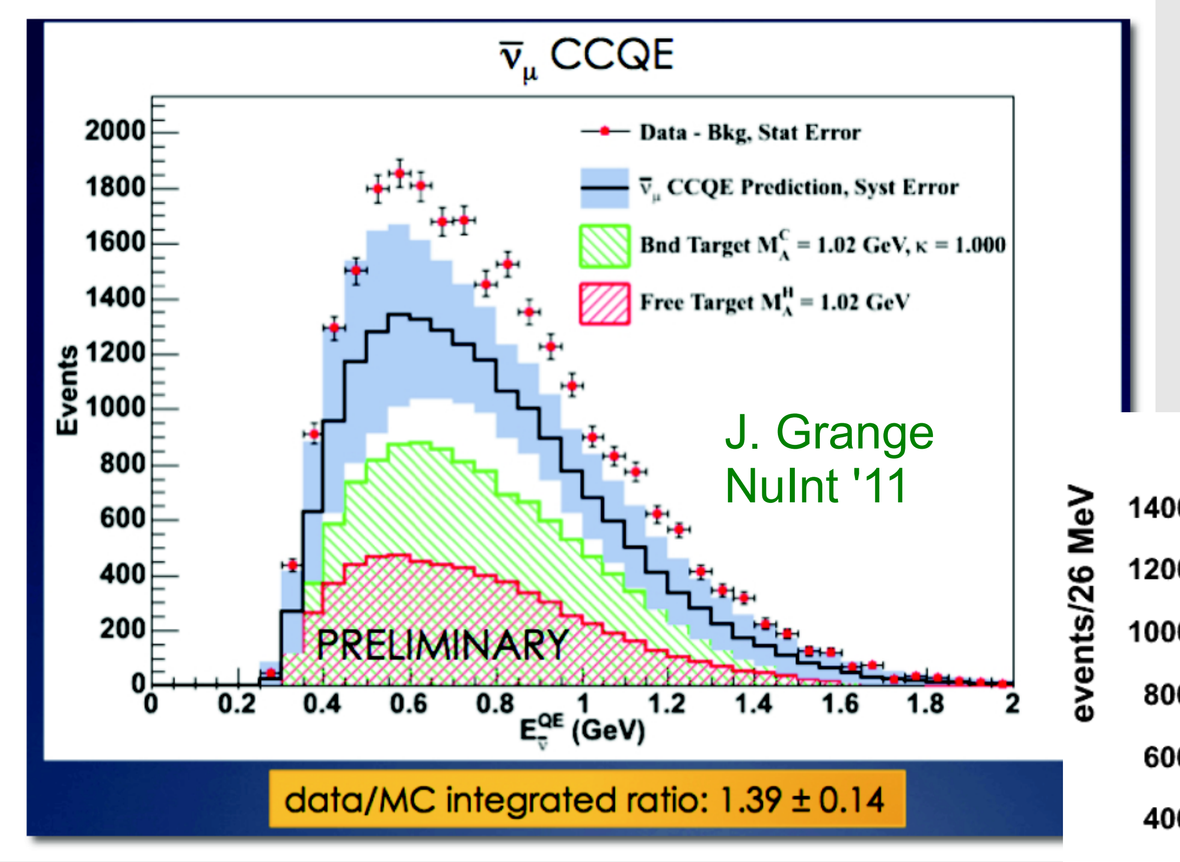
LS model:

– LS model with MB M_A

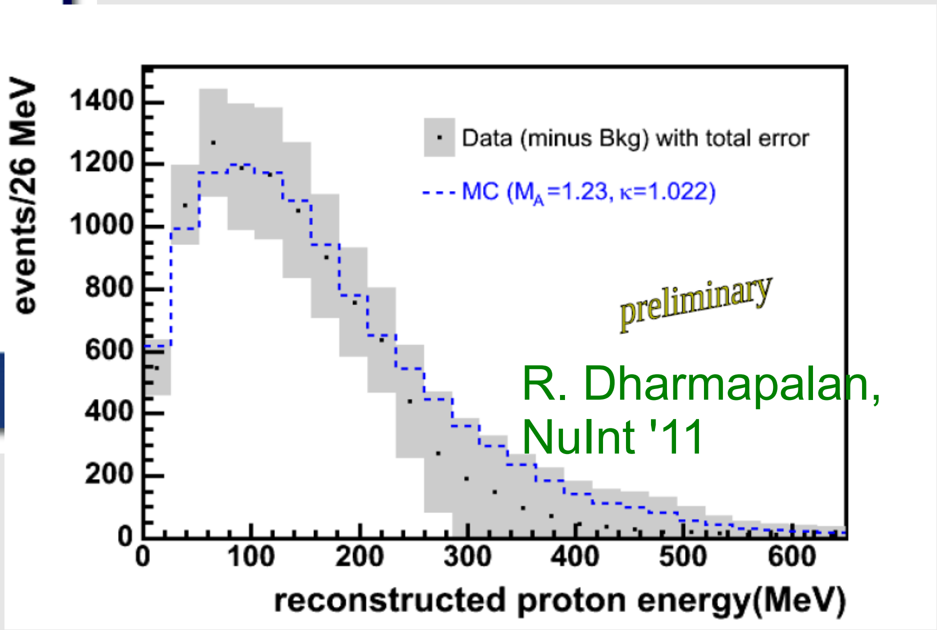
– LS with world ave M_A and extra (non-interfering) term

upcoming MB results: $\bar{\nu}$ CCQE

Preliminary results: $\bar{\nu}$ CCQE



$\bar{\nu}$ NCel



Final MiniBooNE $\bar{\nu}$ CCQE (J. Grange, Florida) and $\bar{\nu}$ NCel (R. Dharmapalan, Alabama) .. coming soon..

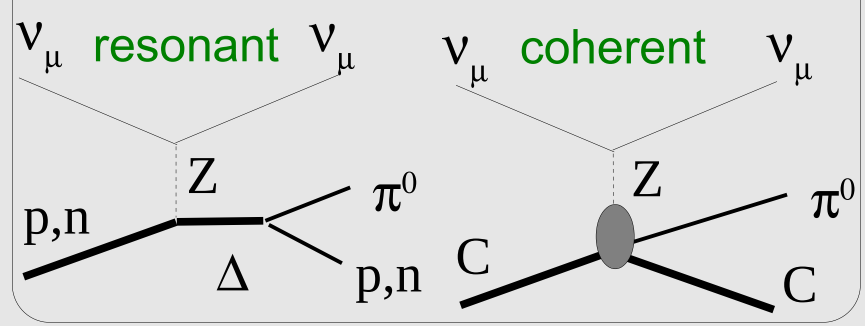
NCπ⁰ production

- ν NC production of neutral pions
  - very important oscillation background
  - complementary to CC pion production
  - sizable coherent piece

- MiniBooNE has produced differential cross section on NCπ⁰ production, used to constrain oscillation search background (NCπ⁰ misID and NCγ)

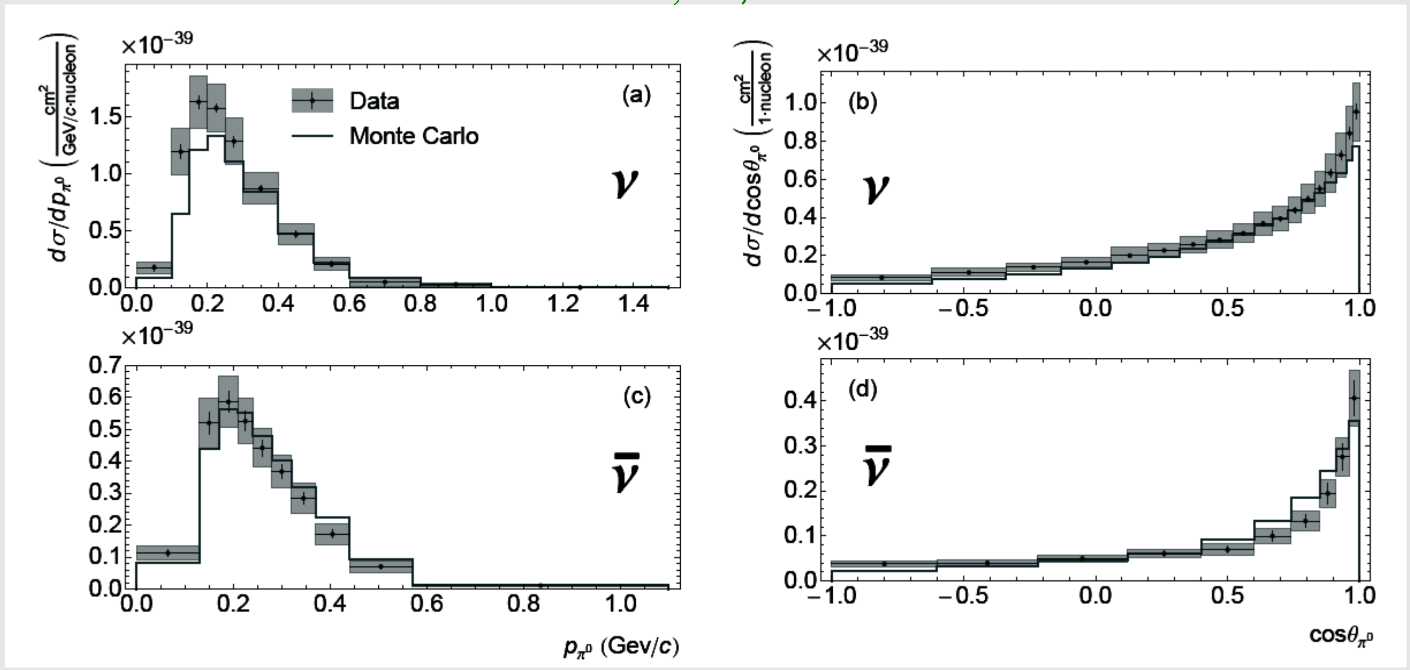
- also SciBooNE results

$$\nu_\mu(p,n)\rightarrow\nu_\mu(p,n)\pi^0,\pi^0\rightarrow\gamma\gamma$$



NCπ⁰ production

ν, $\bar{\nu}$, NC π0 differential cross sections

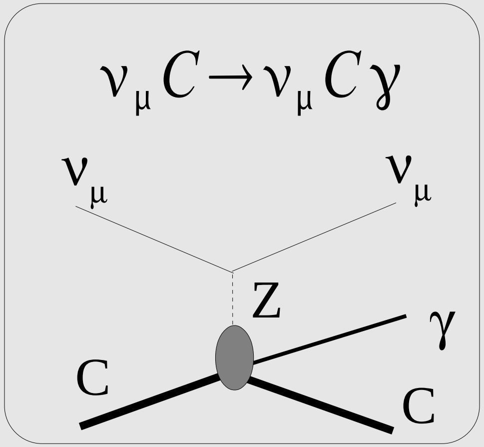


C. Anderson PhD, Yale
PRD81, 013005 (2010)

NC γ production

- ν NC production of photons
  - a possible oscillation background

- MiniBooNE low-energy excess has spurred work on a possible background: NCγ production
- important background for ν_e appearance searches
- eg: R. Hill, Phys. Rev. D 81, 013008 (2010) and e-Print: arXiv:1002.4215 [hep-ph]



NC γ production

TABLE I: Single photon and other backgrounds for MiniBooNE ν-mode in ranges of E_{QE}. Ranges in square brackets are the result of applying a $20-30\%$ efficiency correction.

process	200-300	300-475	475-1250
1γ, non-Δ	85[17 – 26]	151[30, 45]	159[32, 48]
$\Delta \rightarrow N\gamma$	170[34 – 51]	394[79 – 118]	285[57 – 86]
$\nu_\mu e \rightarrow \nu_\mu e$	14[2.7 – 4.1]	20[4.0 – 5.9]	40[7.9 – 12]
$\nu_e n \rightarrow ep$	100[20 – 30]	303[61 – 91]	1392[278 – 418]
MB excess	45.2 ± 26.0	83.7 ± 24.5	22.1 ± 35.7
MB $\Delta \rightarrow N\gamma$	19.5	47.5	19.4
MB $\nu_\mu e \rightarrow \nu_\mu e$	6.1	4.3	6.4
MB $\nu_e n \rightarrow ep$	19	62	249

NC γ production

- more and recent work on this:
  "Weak Pion and Photon Production off Nucleons in a Chiral Effective Field Theory", B. Serot, X. Zhang, arXiv:1011.5913 [nucl-th]

- related to and constrained by π production

- ultimately must understand this process together with pion production in all modes: resonant/non, coherent/non

- may be background for ~1% oscillation probabilities

- should directly search for and/or measure this process.

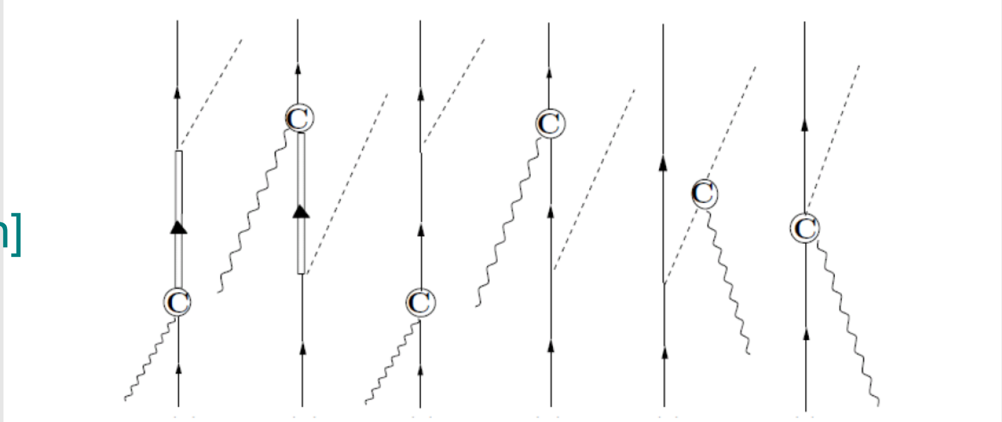


Fig.1: Feymann diagrams for pion production. Change the outgoing pion line to photon line for photon production. C indicates both vector and axial vector currents.

E_{QE}(GeV)	[0.2 , 0.3]	[0.3 , 0.475]	[0.475 , 1.25]
coh	3.1	10.37	5.59
incoh	$6 \times (1.01 + 1.01)$	$6 \times (3.64 + 3.62)$	$6 \times (2.90 + 2.88)$
total	15.22	53.93	40.27
MiniBN	19.5	47.5	19.4

preliminary

Tab.1: NC photon production event's EQE distribution in MiniBooNE for neutrino scattering.

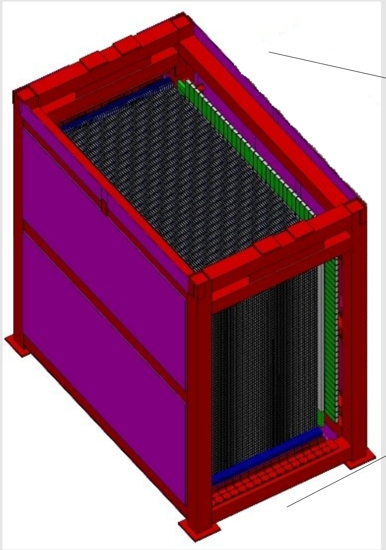
Possible future effort: SciNOvA

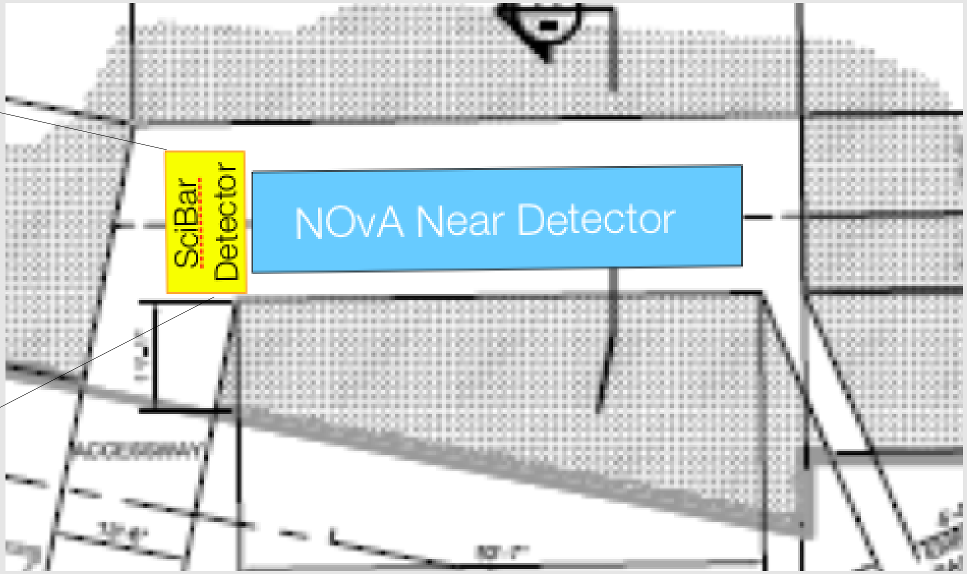
A "SciBar" detector using an existing and proven design (from KEK/SciBooNE), deployed in front of the NOvA near detector in the NuMI off-axis, 2 GeV, narrow-band beam.

A fine-grained SciBar detector in this location will provide:

- important and unique ν scattering measurements including:
  - A test of recent MiniBooNE results indicating anomalously large cross section in CCQE using a different ν source at slightly higher E_ν
  - a search for 2N correlations
  - Neutral-current differential cross sections, $NC\pi^0$, $NC\gamma$ - crucial for ν_e appearance
- significant cross checks of NOvA ν oscillation backgrounds, esp $NC\pi^0$

Cost: $2.4M





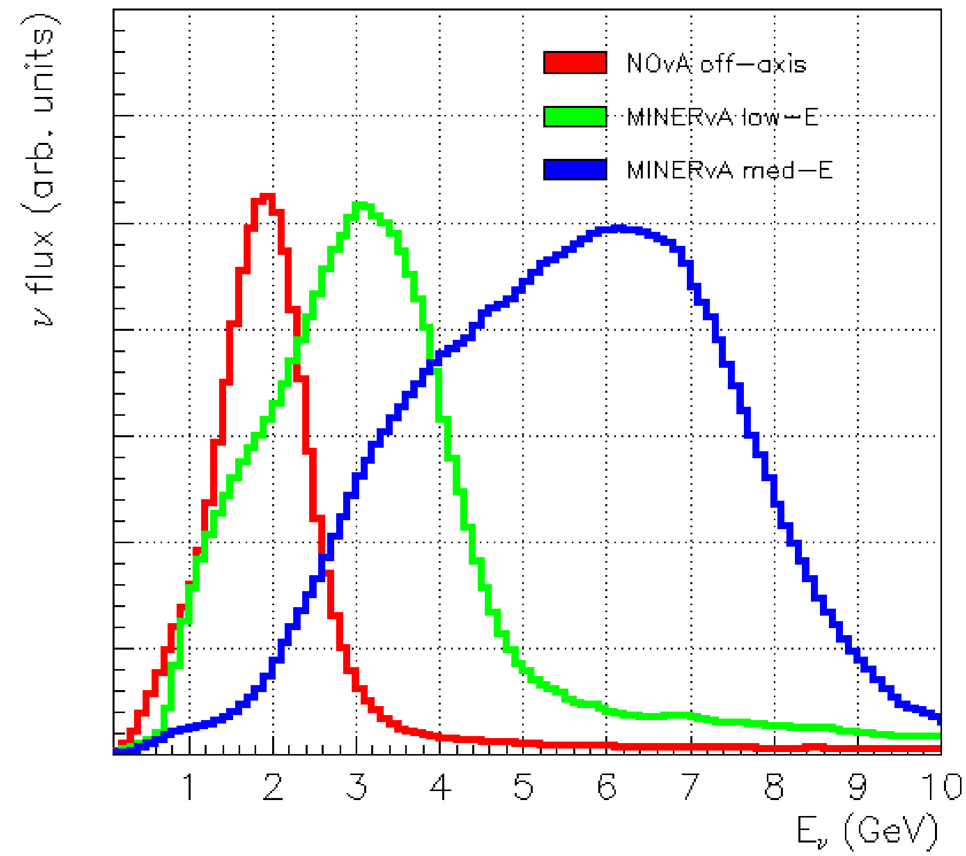
SciNOvA: narrow band beam

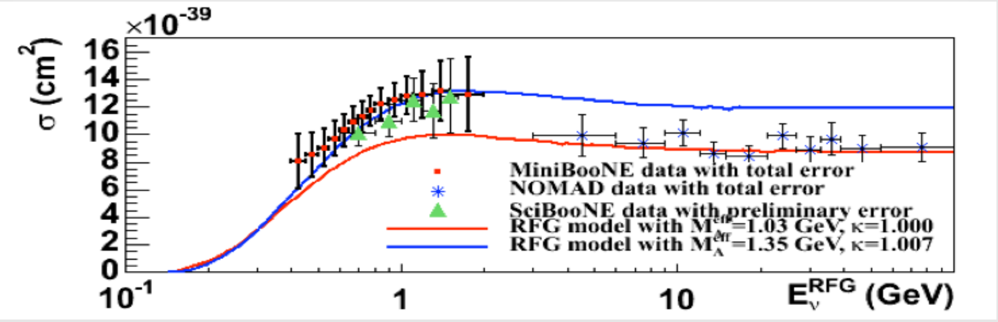
- ~2 GeV mean energy,

- lower energy and smaller energy spread than on-axis flux

- complementary to the NUMI on-axis cross section program

NUMI ν fluxes

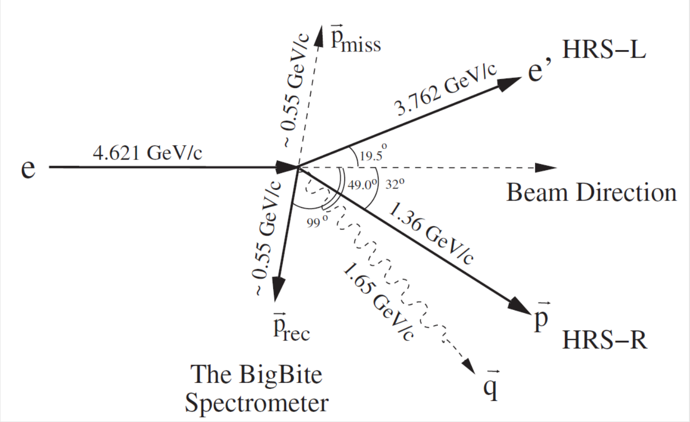




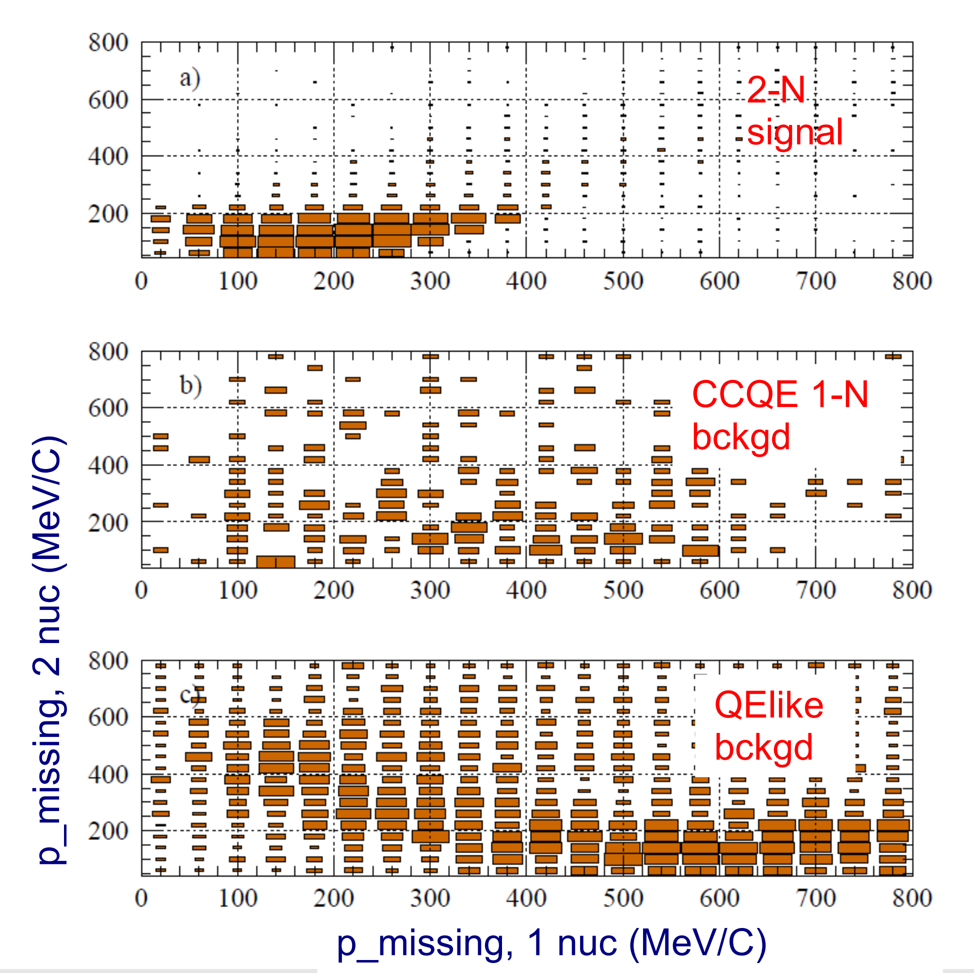
SciNOvA: 2N correlations

- A search for 2 nucleon correlations with SciNoVA is experimentally feasible and would provide the most direct test for MiniBooNE results.

Sketch of experimental method:
- Following method of JLab Hall A experiment:



missing momentum plots



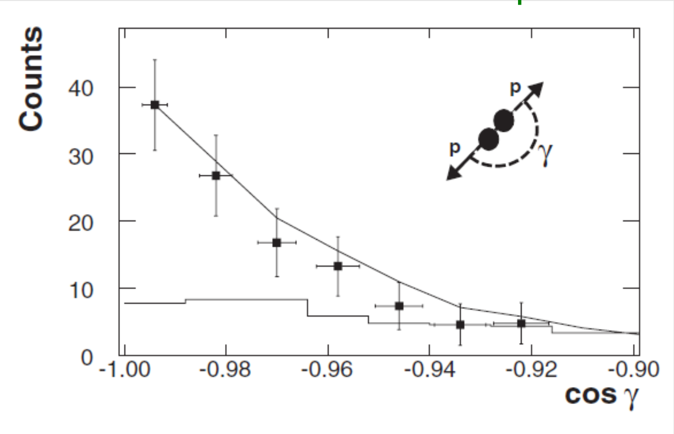
- Find CCQE scattering events with 2 high-momentum recoil nucleons.
- Use transverse kinematics to eliminate neutrino energy unknown (all longnitudinal)
- look for transverse momentum balance when both nucleons considered.
- Separated from more mundane CCQE, CCπ events where energy should be shared with unobserved particles and recoil nucleus.
- Modeled with assumed extra 30% 2N events.

SciNOvA: 2N correlations

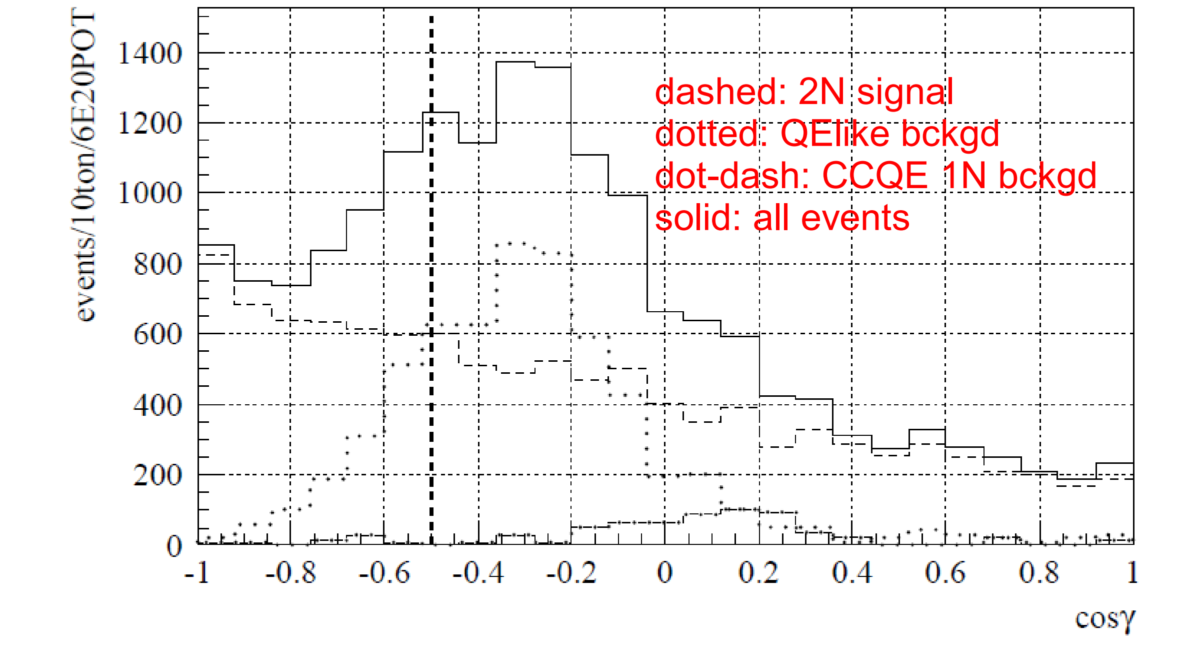
Experimental search with SciNOvA (continued)

- look at cos γ ,angle between 2 nucleons

from JLAB experiment



cos γ distribution



- Resulting, signal/background ~ 3...

- a sensitive search for this process

- and an important experimental constraint.

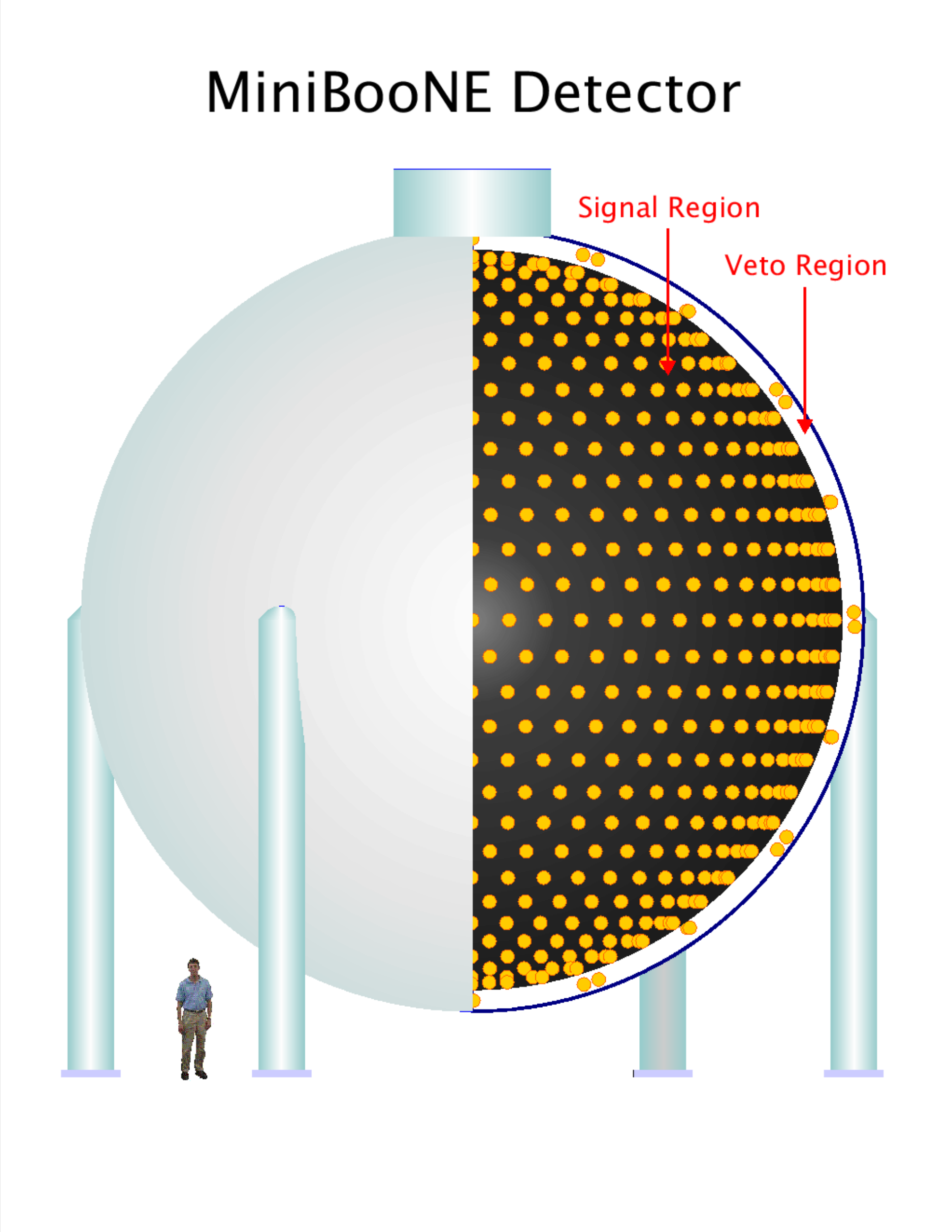
event totals past 2-N cuts

event type	events/10ton/6E20
2-nucleon signal	4119
CCQE 1-nucleon background	65
QElike background	1320
total background	1384

Summary/Conclusions/Outlook

- MiniBooNE ν scatering results have revealed interesting new insights.

- ν charged-current (CC) quasielastic (CCQE)
  - xsection anomously high, 2N effects?
  - MB $\bar{\nu}$ measurement coming soon
  - MINERvA, perhaps SciNOvA
- ν neutral-current (NC) elastic (NCel)
  - consistent with CCQE
  - MB $\bar{\nu}$ measurement coming soon
- ν CC production of π^+, π^0
  - also large cross section consistent with CCQE
- ν CC inclusive scattering
  - MB results coming soon
- ν NC production of neutral pions
  - measurements constrain oscillation backgrounds
- ν NC production of photons
  - an interesting, important channel
  - should pursue further w/ theory and experiment

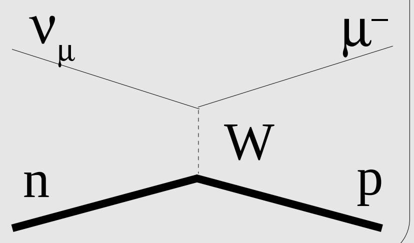


backup slides

modeling ν QE scattering

ν_μ CCQE

$$\nu_\mu n \rightarrow \mu^- p$$



The canonical model for the ν QE process is fairly simple.
Based on impulse-approximation (IA) together with rel Fermi gas (RFG).

- start with Llewellyn-Smith formalism for differential cross section:

$$\frac{d\sigma}{dQ^2}\left(\begin{array}{c}\nu_l + n \to l^- + p\\ \bar{\nu}_l + p \to l^+ + n\end{array}\right) = \frac{M^2 {G_F}^2 cos^2\theta_c}{8\pi {E_\nu}^2}\left\{A(Q^2) \pm B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

- lepton vertex well-known
- nucleon vertex parameterized with 2 vector formfactors (F_1,F_2), and 1 axial-vector (F_A)
- F_1, F_2, F_A (inside of A,B,C) are functions of Q^2 = 4-momentum transfer

- To apply (for a nucleus, such as carbon)
  - assume bound but independent nucleons (IA)
  - use Rel. Fermi Gas (RFG) model (typically Smith-Moniz), with params from e-scattering
  - F_1,F_2 also from e-scattering measurements
  - F_A is largest contribution, not well known from e scattering, but
  - F_A (Q^2=0) = g_A known from beta-decay and
  - assume dipole form, same M_A should cover all experiments.

$$F_A(Q^2) = -\frac{g_A}{\left(1+\frac{Q^2}{M_A^2}\right)^2}$$

- No unknown parameters (1 if you want to fit for M_A)

- can be used for prediction of CCQE rates and final state particle distributions.

- Until recently, this approach has appeared adequate and
  all common neutrino event generators use a model like this..

Summary of M_A from CCQE scattering

- M_A values extracted from various experiments

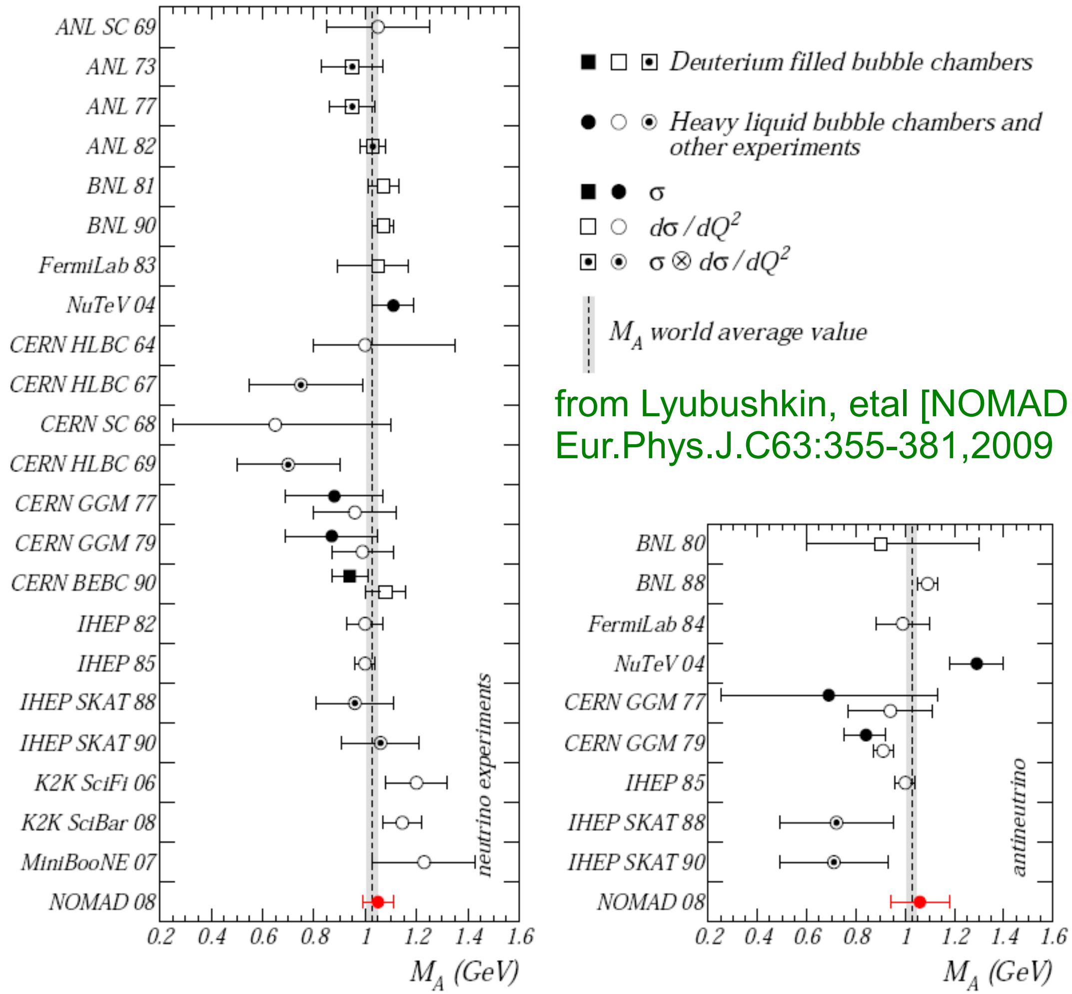
- different targets/energies, fit strategies

- world average (as of 2002)
  M_A=1.026±0.021 GeV
  (Bernard, etal, JPhysG28, 2002)

- Also, M_A from π electro-production similar

- However, recent data from some high-stats experiments (on nuclear targets) not well-described with this M_A . (or perhaps... the physics model).

summary of ν, $\bar{\nu}$ measurements of M_A



from Lyubushkin, etal [NOMAD collab], Eur.Phys.J.C63:355-381,2009

Fig. 18. A summary of existing experimental data: the axial mass M_A as measured in neutrino (left) and antineutrino (right) experiments. Points show results obtained both from deuterium filled BC (squares) and from heavy liquid BC and other experiments (circles). Dashed line corresponds to the so-called world average value $M_A = 1.026 \pm 0.021$ GeV (see review [33]).

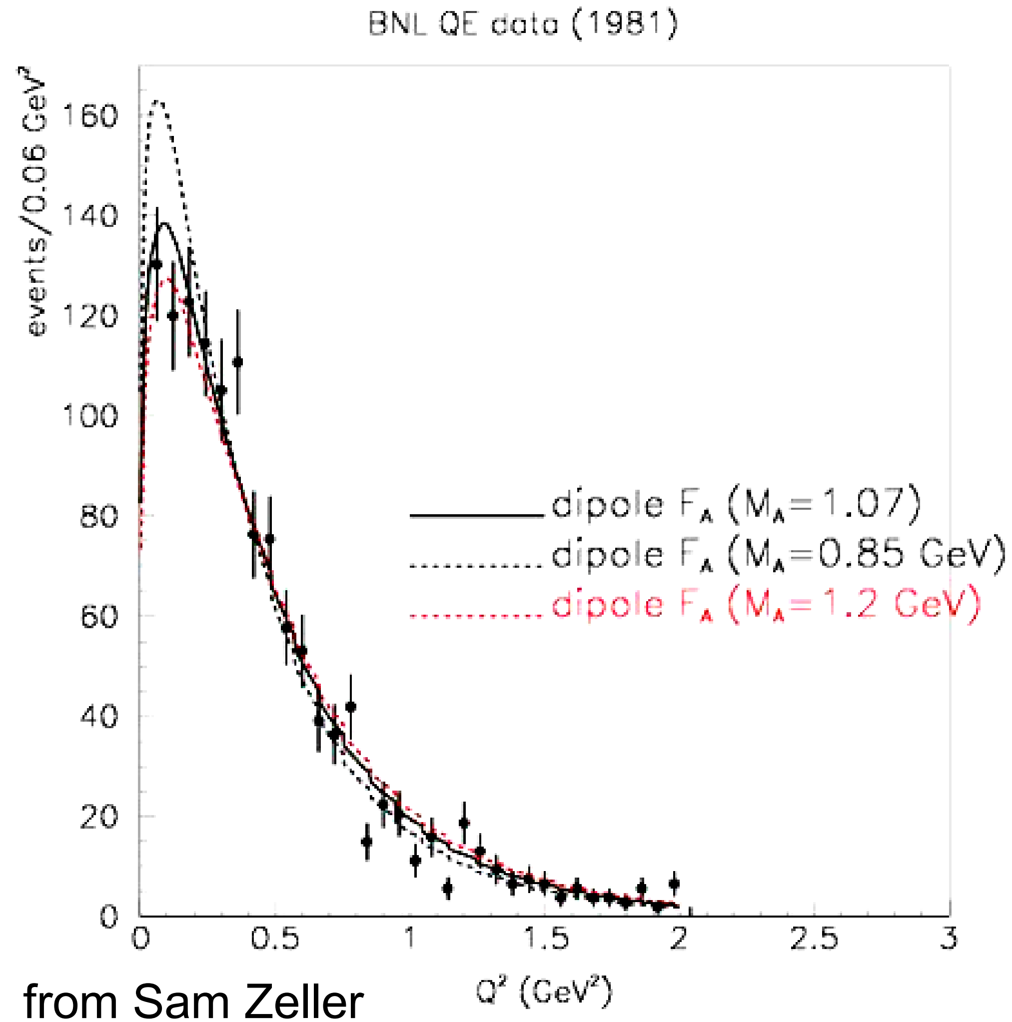
Early CCQE results

For example, BNL CCQE data:
- Baker, PRD 23, 2499 (1981)
- data on D_2
- 1,236 ν_μ QE events
- M_A=1.07 +/- 0.06 GeV

- curves with diff M_A values, relatively norm'd, overlaid.

- M_A extracted from the shape of this data in Q^2

$$F_A(Q^2) = -\frac{g_A}{\left(1+\frac{Q^2}{M_A^2}\right)^2}$$



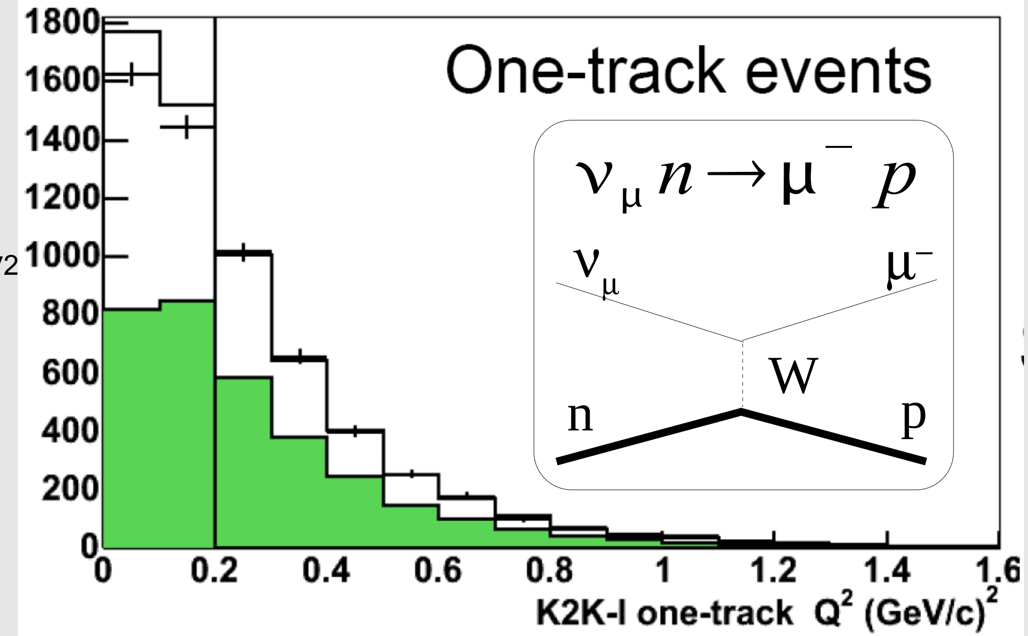
from Sam Zeller

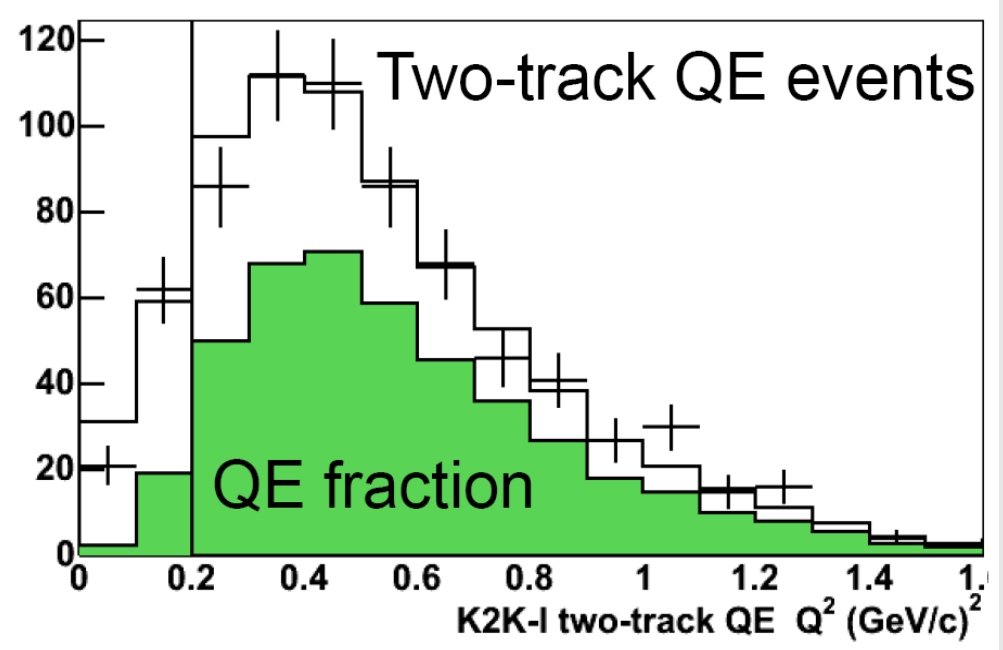
K2K CCQE results

- K2K results from scifi (in water) detector
(PRD74, 052002, '06)

- Q^2 spectrum: more events at Q^2 > 0.2 GeV^2

- shape fit of Q^2 distribution yields
M_A = 1.20±0.12





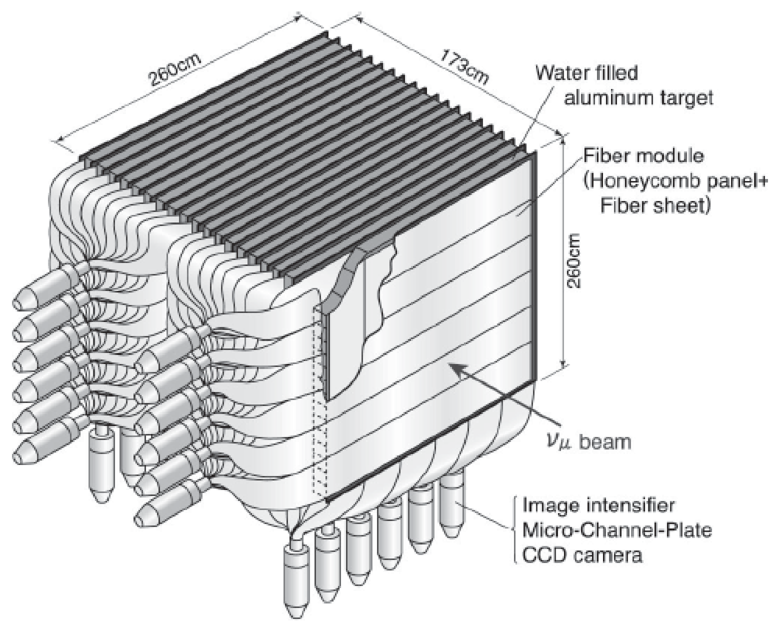


FIG. 2. A schematic diagram of the SciFi detector.

from Rik Gran, Nuint09

First MB CCQE results

- MiniBooNE results (from CH_2)
  (PRL100, 0323021, '08)

- Q^2 spectrum of data, compared to world-average M_A (dashed)
  shows substantial event excess at $Q^2 > 0.2$ GeV^2.
  $\Rightarrow$ requires larger M_A

- Also event deficit at $Q^2 < 0.2$ GeV^2
  $\Rightarrow$ requires new parameter, κ, to increases "Pauli-blocking" of FS nucleon

- shape-only fit of Q^2 distribution yielded:

$$\boxed{\begin{aligned} M_A^{\rm eff} &= 1.23 \pm 0.20 \text{ GeV}, \\ \kappa &= 1.019 \pm 0.011. \end{aligned}}$$

- "eff" = effective to acknowledge possible nuc. effects.

- fit with Q2 > 0.2 GeV^2 yields:
  M_A=1.25±0.12 GeV

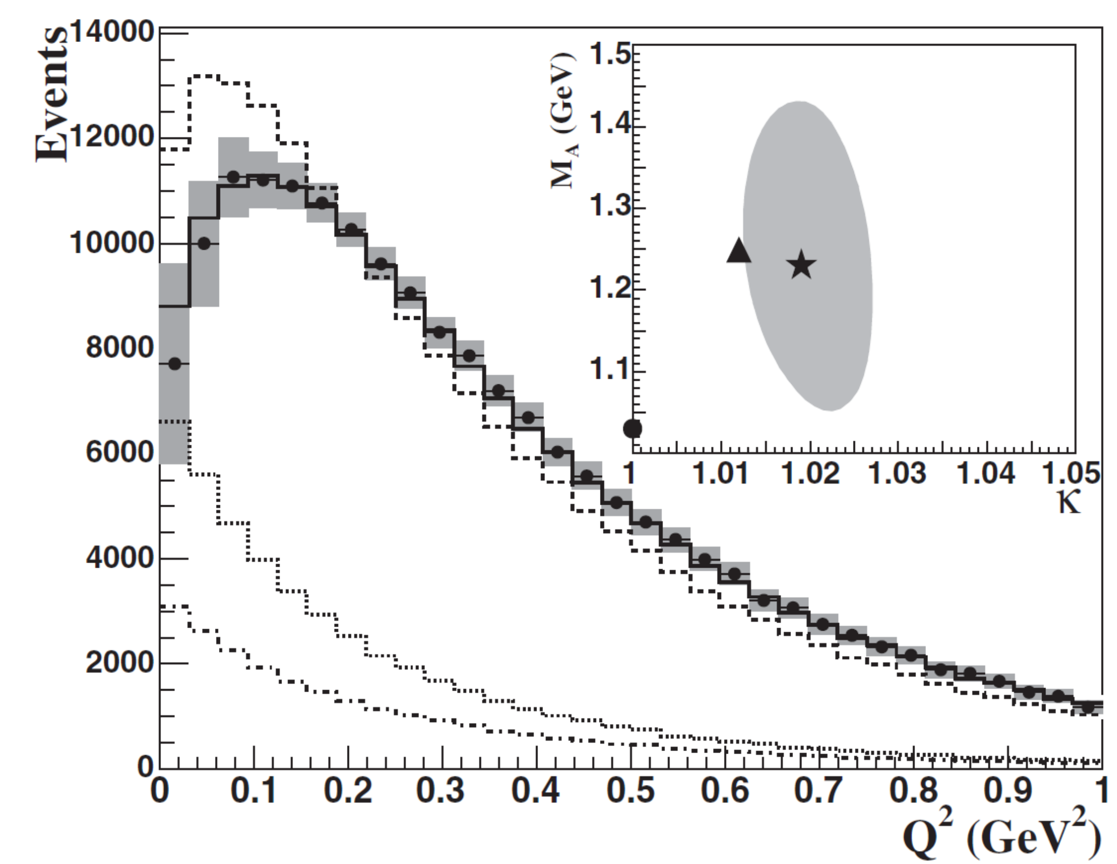


FIG. 2. Reconstructed Q^2 for ν_μ CCQE events including systematic errors. The simulation, before (dashed curve) and after (solid curve) the fit, is normalized to data. The dotted curve (dot-dashed curve) shows backgrounds that are not CCQE (not "CCQE-like"). The inset shows the 1σ C.L. contour for the best-fit parameters (star), along with the starting values (circle), and fit results after varying the background shape (triangle).

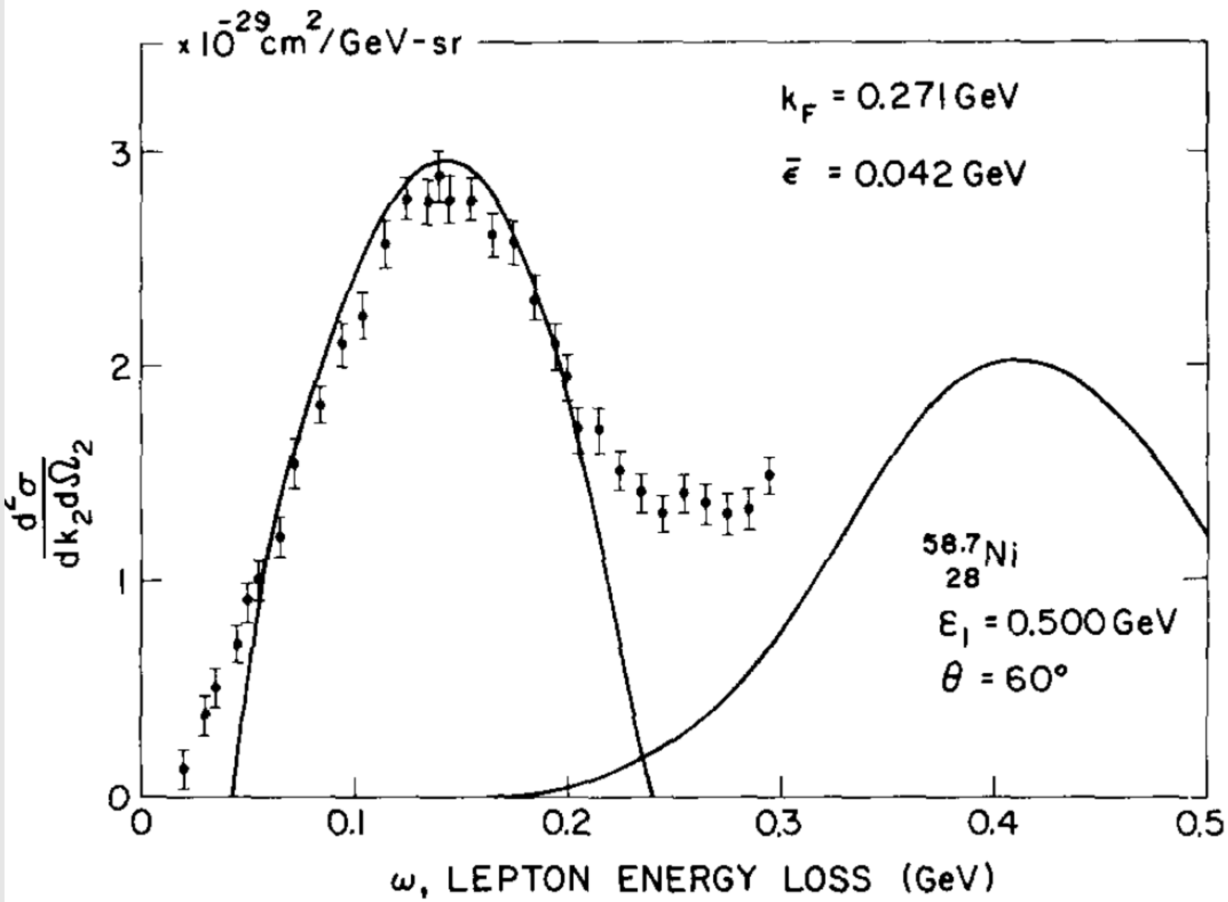
modeling ν QE scattering

8.C.2 Nuclear Physics B43 (1972) 605-622. North-Holland Publishing Company

NEUTRINO REACTIONS ON NUCLEAR TARGETS ‡

R. A. SMITH ‡‡ and E. J. MONIZ ‡‡‡
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

Received 15 December 1971
(Revised 29 February 1972)



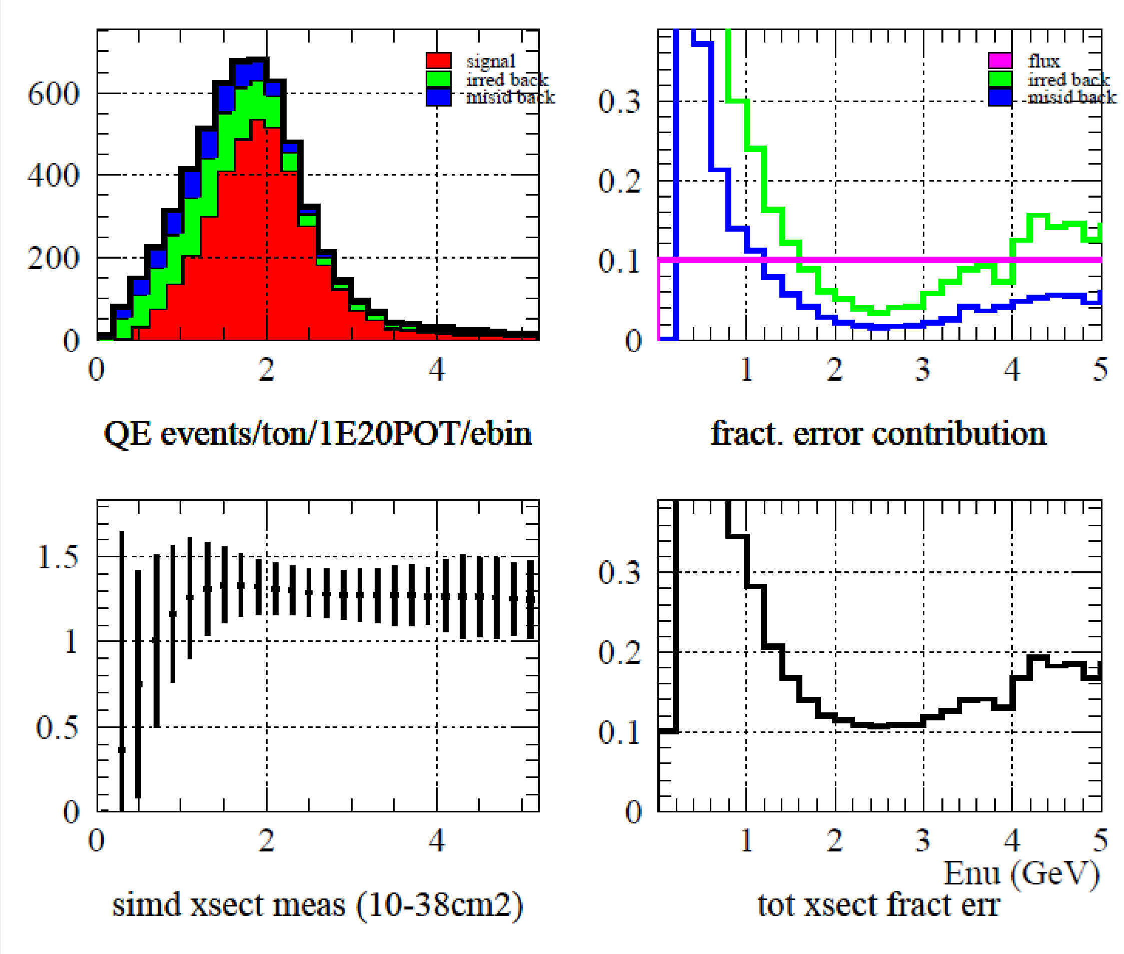
SciNOvA CCQE scattering measurement

Estimated errors on SciNOvA CCQE total cross section measurement

- estimated with bootstrapping from MiniBooNE error analysis
- checked by predicting actual MiniBooNE errors
- dominant background is CCπ feeddown from high "true" E_ν to lower recon'd E_ν due to lost pion (in detector medium or nucleus)

- resulting error at 2 GeV (flux-peak of NOvA beam) is 12%

- will provide important points in CCQE total cross section data and most-directly check MiniBooNE results



all plots as function of reconstructed E_ν (GeV)

NC photon production

- should be possible (at higher rate experiments) and should be pursued
- SciNOvA event rates
- ~ equal to full MiniBooNE neutrino sample (but in 10 tons).
- NCγ cross sections are calculated to be O(10^{-3}) that of CCQE (from Hill or Serot/Zhang)
- resulting in sample of O(100) events in MB (same as 0.1% oscillations)
- SciNOvA will collect O(100) events of this type if calculations are correct
- photon recon down to ~100MeV and comparison with NCπ^0 channel allows a measurement of NCγ
- together with NCπ^0 channel will lend crucial info to ν_e appearance search (NOvA and others)

SciNOvA ν kevent/yr (6E20POT) in 10 ton fiducial vol

	Charged-current	Neutral-current
elastic	220	86
resonant	327	115
DIS	289	96
coherent	8	5
total	845	302
$\nu + A \to \pi^0 + X$	204	106

photon energy in NCπ^0 event in scibar/SciBooNE

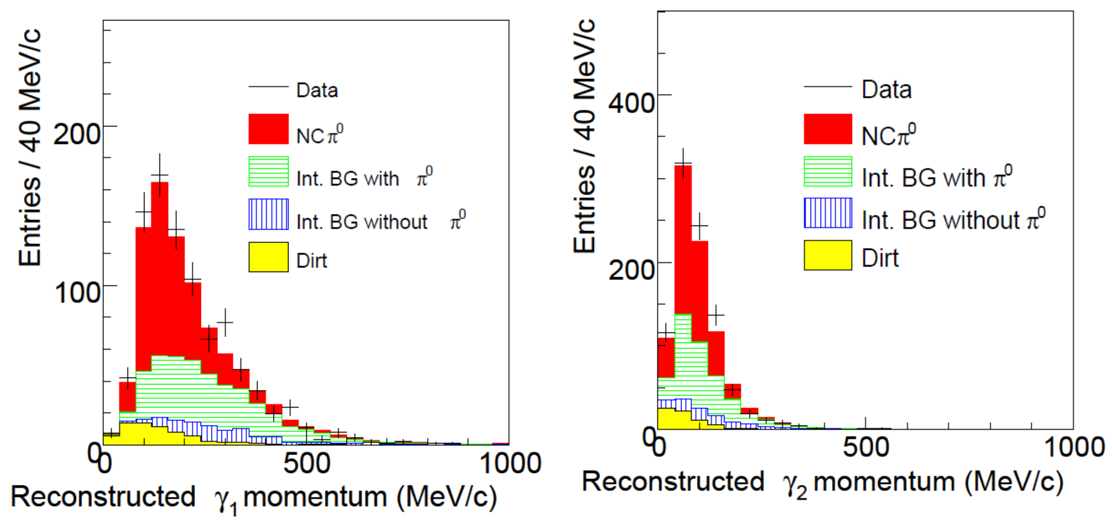
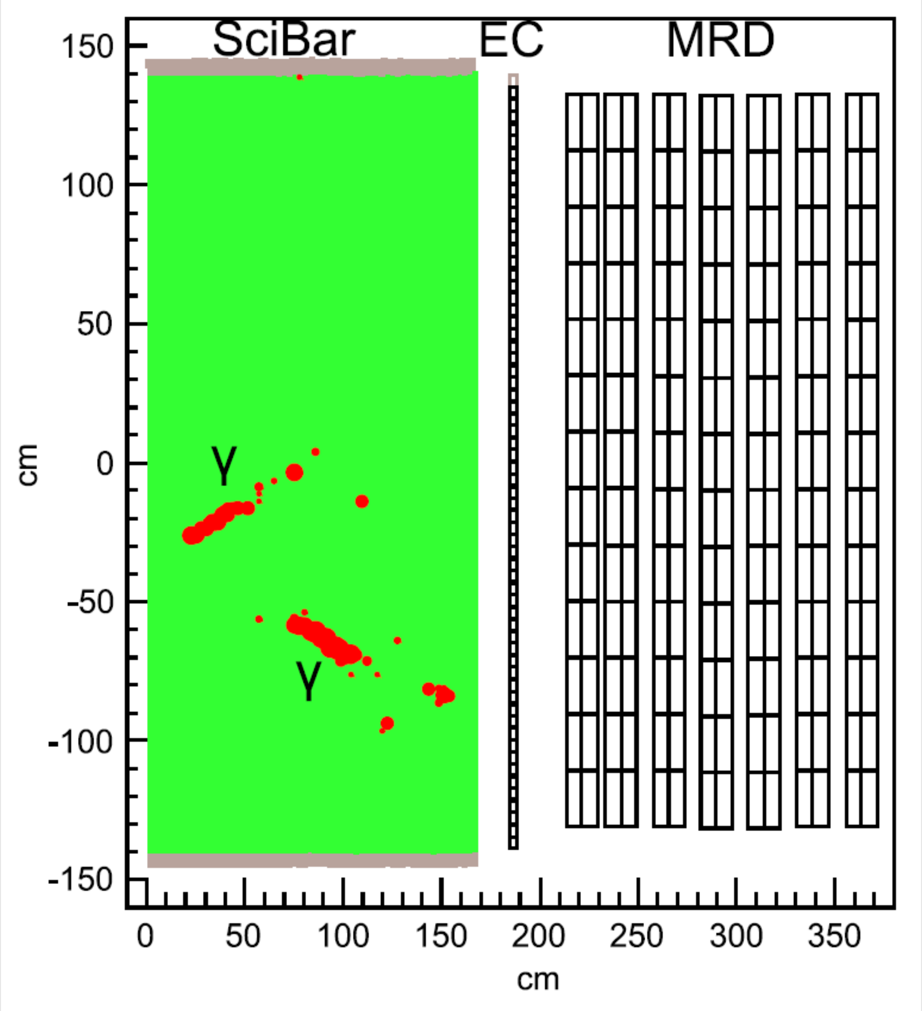


Figure 6.4: $E^{rec}_{\gamma 1}$ and $E^{rec}_{\gamma 2}$ before the π^0 mass cut ($E^{rec}_{\gamma 1} > E^{rec}_{\gamma 2}$)

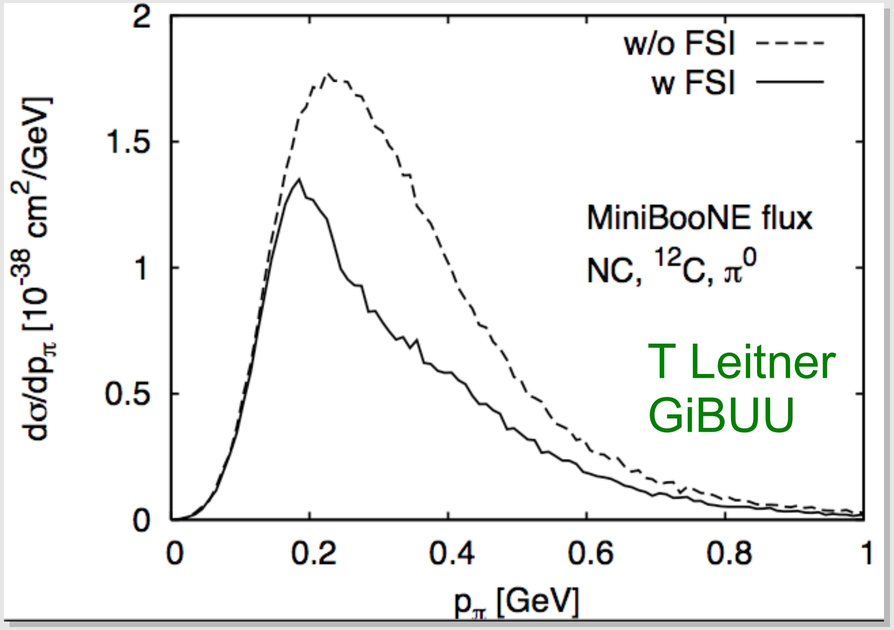
Measuring NC photon production

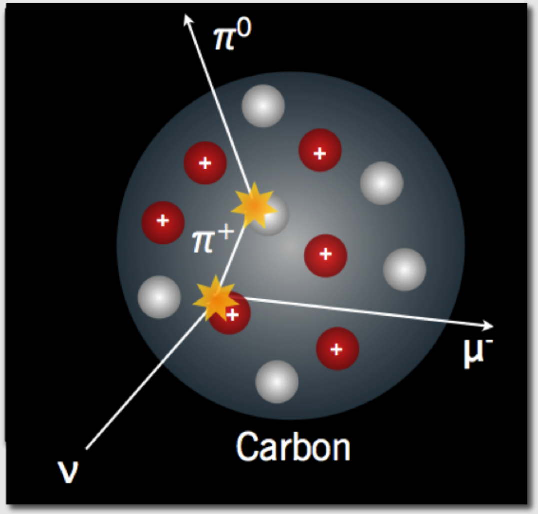


Final State interactions in nN

Might wonder about how FSI in nucleus of nucleons, pions may effect this story.

Good question... as they are not small...





in brief, they are modeled in state-art generators with guidance from theory,
and constrained by nucleon, pion, scattering data,
but had better also understand nu pion production channels..